NASA Technical Paper 1423

Flight Investigation of Piloting Techniques and Crosswind Limitations Using a Research-Type Crosswind Landing Gear

Bruce D. Fisher, Perry L. Deal,
Robert A. Champine, and James M. Patton, Jr.

MAY 1979

NASA

NASA Technical Paper 1423

Flight Investigation of Piloting Techniques and Crosswind Limitations Using a Research-Type Crosswind Landing Gear

Bruce D. Fisher, Perry L. Deal,
Robert A. Champine, and James M. Patton, Jr.
Langley Research Center
Hampton, Virginia

NASA
National Aeronautics
and Space Administration

Scientific and Technical
Information Office

1979

SUMMARY

A flight research program was undertaken by the National Aeronautics and Space Administration (NASA) to investigate the problems associated with landing a light STOL transport in strong crosswind conditions with a research-type, crosswind landing gear. This program was a continuation of an earlier program where the same airplane with its conventional, tricycle landing gear was used. With the crosswind landing gear used in this program, crosswind landings were made with crosswind magnitudes of 25 to 30 knots; whereas with the conventional, tricycle landing gear used in the earlier program, the crosswind limits were 15 to 20 knots. Throughout this paper the term "crosswind" means direct crosswind component, with a crosswind from the right being a positive value.

Three landing-gear modes were studied: preset, automatic, and castor. Presetting the landing gear to a fixed crab angle prior to touchdown was found to be an undesirable method of operation because the pilots did not have sufficient information to predetermine the proper crab angle. The automatic mode was limited somewhat by the inadequate compass-system response rate in turbulent conditions. The castor mode of operation for the crosswind landing gear (passive self-alignment) was preferred by the pilots for operation in severe crosswinds. In a castor-mode landing, the pilots would apply the main-gear castor locks after the gears had passively self-aligned with the direction of travel; then, they would use nose-wheel steering and some brakes during the ground roll-out.

The conclusions reached in this study are for this particular STOL airplane with research-type, crosswind landing gear.

INTRODUCTION

In the flight research program reported in reference 1, piloting techniques and crosswind limitations were studied for a light STOL airplane making crosswind landings with the production, conventional, tricycle landing gear. The results of that program indicated that control during ground roll-out was the most critical problem and that aerodynamic control in flight required for slip or decrab may limit roll-out control. These results led to the conclusions that a crosswind landing gear should be considerably safer and that the crosswind limits could be significantly increased. Throughout this paper the term "crosswind" means direct crosswind component, with a crosswind from the right being a positive value.

Based on the flight experience gained in the study of reference 1 and on model studies of several crosswind-landing-gear systems reported in reference 2, a research-type crosswind-landing-gear system was designed and installed on the airplane. In addition, wing-lift spoilers and rudder-pedal steering of the nose gear were incorporated. NASA then conducted a flight-test program of the modified airplane. The objectives of the program were to evaluate and demonstrate

the effectiveness of lift spoilers and various modes of crosswind-landing-gear operation in extending the crosswind landing limits of the airplane. Preliminary results of this program were reported in reference 3, which contains a summary of NASA landing-gear research; the final results of this program are reported herein.

SYMBOLS AND ABBREVIATIONS

Except for airspeed and wind speed, which are given in knots (1 knot = 0.5144 m/sec), data are presented in both SI and U.S. Customary units. The measurements and calculations were made in U.S. Customary Units. Factors relating the two systems of units are given in reference 4.

$a_{y,td}$	lateral acceleration measured at airplane center of gravity at touchdown, positive for acceleration to right, g units ($1g = 9.806\ m/sec^2$)
STOL	short take-off and landing
VFR	visual flight rules
V_{SO}	landing configuration stall speed, full flap, knots
V_{td}	indicated airspeed at touchdown, knots
β	angle of sideslip, positive for right sideslip, deg
δ_a	total aileron deflection, positive for left roll, deg
δ_{crab}	crab angle, positive for airplane nose left of runway center line, deg
$\delta_{crab,td}$	crab angle at touchdown, positive for airplane nose left of runway center line, deg
δ_{mg}	main-gear offset angle, positive for gear rotated to right of airplane center line, deg
$\delta_{mg,td}$	main-gear offset angle at touchdown, positive for gear rotated to right of airplane center line, deg
δ_{ng}	nose-gear offset angle, positive for gear rotated to right of airplane center line, deg
δ_r	rudder deflection, positive trailing edge left, deg
θ_{td}	pitch attitude at touchdown, positive for nose up, deg
φ	bank angle, positive for right bank, deg
ϕ_{td}	roll attitude at touchdown, positive for right roll, deg

EQUIPMENT AND PROCEDURES

Test Airplane

The test airplane was a high-wing, twin-turboprop light transport previously described in reference 1 and subsequently modified for this program. The maximum design gross weight was 48 928 N (11 000 lb), with the aircraft weight ranging between 38 253 and 45 370 N (8600 and 10 200 lb) during the tests. The airplane modifications added very little weight and did not shift the longitudinal center of gravity of the airplane.

A dimensioned three-view drawing of the airplane as modified for this program is given as figure 1. The modifications included replacing the fixed landing gear with a research-type, crosswind landing gear, incorporating nose-gear steering with the pilot's rudder pedals, and adding wing-lift spoilers. The flap system, engine characteristics, and basic aerodynamic controls were unchanged from those described in reference 1. The crosswind-landing-gear and wing-lift spoiler systems are described in the next section.

Crosswind-Landing-Gear and Wing-Lift Spoiler Systems

The original, single main wheels were replaced by the dual wheel units from a military helicopter; each wheel rotated independently of the others. The main-gear legs of the transport were inverted, the right and left legs were interchanged, and a new nose wheel and fork were installed. This change lowered the fuselage reference line and vertical center of gravity about 15.2 cm (6 in.) and reduced the tail clearance angle from 10.5° to 8.5°. The crosswind landing gear is shown in more detail by the drawing in figure 2 and by the photograph and dimensioned drawing in figure 3. The main-gear units were physically interconnected by metal tie rods (figs. 2 and 3) to insure that the main-gear units were tracking together and to facilitate the centering of the gear. The original landing-gear rubber spring blocks were replaced by rigid links shown in figure 2. Instead of using the rubber spring blocks, the research-type crosswind landing gear used a spring mechanism which is shown in figure 3. The dual main-gear axle was trailed behind a horizontal pivot, and the vertical motion was controlled by a liquid spring (liquid-filled strut) mounted between the axle and a point above the pivot. The research-type crosswind-landing-gear system was designed to provide several modes of operation and was not optimized for weight, aerodynamics, or operational simplicity. There was no antiskid system for these tests. The main and nose gear could be pivoted $\pm 30^{\circ}$ for crosswind landings.

The crosswind-landing-gear system was designed to provide the capability of investigating three crosswind-landing-gear concepts: preset, automatic, and castor. The three modes of operation are outlined in table I.

In the preset mode, the pilot had to set the gear to the desired offset angle prior to touchdown by means of a tiller-bar control in the cockpit. (See fig. 4.) The tiller bar, which controlled the pivot angle of the gear, was located on the control column behind the pilot's control wheel. After the main

gear had been locked following touchdown, the tiller bar could steer only the nose gear. (This was the purpose of the tiller bar in the unmodified airplane.)

In the automatic mode (active self-alignment), the gyrocompass system was used to generate an error signal proportional to the angle between a selected runway heading and the airplane heading. This signal, summed with a main-gear position feedback signal, was used to automatically keep the gear aligned with the runway center line while in flight.

In the castor mode, the landing-gear system was free to align with the direction of travel at touchdown (passive self-alignment). However, to prevent the airplane from veering off the runway, the main gear had to be locked in the position existing shortly after touchdown and nose-wheel steering then initiated.

In all modes, the main gear was locked in position by a hydraulic castor lock on each main-gear unit. (See fig. 3.) In the preset and castor modes, the main gear was locked in position by pressing a switch on the pilot's control wheel. (See fig. 4.) In the preset mode, the castor locks were actuated prior to touchdown by the control-wheel switch alone. In the castor mode, the castor locks activated only when both the control-wheel switch was depressed and both main-gear squat switches (fig. 3) were activated. In the automatic mode, the gear was locked in position after either of the two main-gear squat switches were compressed by the weight of the airplane without requiring the pilot to press the switch. The main gear had to be locked or restrained in order to develop nose-wheel steering capability.

In any landing-gear operational mode, after a squat switch on the nose gear had been activated, the pilot could select rudder-pedal steering of the nose gear by depressing and holding a thumb switch on the pilot's control wheel. This switch was adjacent to the main-gear castor-lock switch shown in figure 4. The maximum differential nose-wheel travel with rudder-pedal steering was from -3° to 3° about the nose-wheel setting at time of actuation. This feature was incorporated to allow the pilot to have limited-nose-wheel steering for the high-speed part of the ground roll without having to release the control wheel or throttle to reach the tiller bar.

The pilot could also center the gear in any mode by pushing a single switch on the crosswind-landing-gear control panel shown in figure 4. The gear centering command overrode all other inputs or actions. The main gear centered through hydraulic action on the tie rod through the centering cylinder shown in figure 2. During centering, a position signal was fed to the nose-gear actuator so that the nose gear would follow the angular position of the main gear.

The conventional aerodynamic (rudder and aileron) and low-speed nose-wheel steering controls were retained from the original airplane. Main-gear braking effectiveness was greatly reduced because hard braking caused flat spots or blown tires. Apparently, with the airplane heeling, one of the dual wheels did not carry sufficient load to overcome brake torque and skidded, which caused a flat spot on that tire. Reverse thrust became the principal braking control although very little actual engine power was developed because of the slow engine response. (See ref. 1.)

A crosswind-landing-gear position indicator was developed for this program. The location of the indicator in the airplane instrument panel is shown in figure 4, and a schematic of the indicator is shown in figure 5. The gyrocompass card was driven by a gyro slaved to the compass heading. The double-bar needle was set by the pilot to the magnetic heading of the landing runway. The angular difference between the airplane heading and the runway magnetic heading (double-bar needle) was the crab angle of the airplane. The single-bar needle indicated the angle of the landing gear with respect to the airplane center line. When the landing gears were properly aligned with the runway center line, the single-bar and double-bar needles were superimposed. In the example given in figure 5, the runway heading and landing-gear position are purposely shown misaligned. The airplane is shown flying to a heading of 350°, crabbed 15° to the right of runway center line. The landing-gear system is shown with an offset of 20° to the left of airplane center line, which means that the landing gears have been rotated 5° too far. In the preset mode, the pilot used the tiller bar to correct the error and bring the landing gear into alignment with the runway (single needle superimposed on the double needle). In the automatic mode, needle misalignment indicated a system malfunction. Some airplanes with preset crosswind landing gear have been known to have actually landed with the landing gear set in the wrong direction. The use of this indicator should prevent such an occurrence unless an unusually severe wind shift were to occur prior to touchdown but after the landing gears were set. The pilot could easily determine proper wheel alignment by a quick glance without mentally processing information to relate heading and landing-gear-alignment magnitude and direction. Further details on the crosswind-landing-gear position indicator may be found in reference 5.

The wing-lift-spoiler system (fig. 1) consisted of hydraulically actuated panels on the upper surface of each semispan. The system was automatically limited to deployment at touchdown by means of main-gear squat switches in series with an arming switch and a throttle position switch. The squat switch for the left main gear can be seen in figure 3. Each spoiler was 7.7 percent of the wing chord, with the leading-edge pivot at 76 percent of the wing chord. The length of each lift-spoiler set was 31.8 percent of the wing semispan, with the inboard end at 29 percent of the semispan.

Data Acquisition

Thirty-two parameters were recorded onboard the aircraft by a magnetic-tape data system at 80 samples/sec by a pulse code modulation method. All data were correlated by a time code. An automatic ground-based data system was used to produce time histories of the desired data. The parameters included angle of attack; angle of sideslip; altitude; airspeed; control surface deflections; pitch angle; roll angle; heading angle; linear acceleration about the X-, Y-, and Z-axes of the airplane; angular velocity about the X-, Y-, and Z-axes of the airplane; throttle position; engine torque for each engine; engine speed for each engine; main-gear angle; nose-gear angle; airplane crab angle; rudder-pedal-steer switch position; gear-centering switch position; and main-gear-lock-selected switch position.

Airspeed, angle of attack, and angle of sideslip were measured with the probe described in reference 1. The probe, and the nose boom upon which the probe was mounted, are shown in figure 1. Nose-gear angle was taken from a position potentiometer on the nose-gear strut, and main-gear angle was taken from a position potentiometer on the right main gear. Airplane crab angle was taken from that part of the compass system which supplied crab angle to the pilot's crosswind-landing-gear position indicator in the cockpit. The touch-down position, ground-roll distance, maximum lateral dispersion on roll-out, and wind-data measurements are described in the following section.

Test Facility

VFR STOL crosswind landings were made at the airfield shown in figure 6. The field elevation is 12.5 m (41 ft). Landings were made on all runways, depending on wind direction, to get the desired crosswind conditions. This airfield is the same as that used in the program reported in reference 1.

STOL runway markings, as described in reference 6 and illustrated in figure 7, were painted on the existing runways. The STOL runways were 30.5 m (100 ft) wide and 457 m (1500 ft) long. The painted lines were 0.305 m (1 ft) wide, except for the longitudinal lines in the target touchdown zones; these were 0.61 m (2 ft) wide in order to enhance visibility. The three runways on which the STOL runway markings were painted were 1524 to 2743 m (5000 to 9000 ft) long and 46 to 61 m (150 to 200 ft) wide.

The landings were made at an approach angle of 3° or 6°. The angle was indicated by the visual guidance system described in reference 1. The visual guidance system was placed beside the runway, far enough ahead of the target touchdown zone that with the combined glide path and a nominal flare, the pilot could guide the airplane to the target touchdown point shown in figure 7.

Markers were placed along the runway edge at intervals of 30.5 m (100 ft) to aid the observers in the control tower in estimating the longitudinal touch-down point, the stopping distance, and the point at which the maximum lateral dispersion occurred.

Lateral touchdown dispersion and maximum lateral ground roll-out disper-sion were computed from calibrated video records of the landings. Each land-ing was recorded on a video tape recorder whose signal was taken from a camera located on the extended runway center line and facing the oncoming aircraft. The camera, shown in figure 8, was located 206 m (675 ft) from the end of the STOL runway (fig. 7). A typical video picture is shown in figure 9. The ver-tical grid, which was electronically superimposed on the picture, was scaled at several known points along each STOL runway to determine the variation of scale factor with distance of the airplane from the camera location. By use of this distance information and the longitudinal distances obtained from the observers in the control tower, the lateral touchdown dispersion and the maximum lateral ground roll-out dispersion were determined. As a further means of correlating

the airplane-measured data with the video data, Greenwich mean time was also superimposed on the picture in either of the upper corners.

Wind direction and magnitude were measured at five elevations on a wind-sensor tower located at the central landing-field position shown in figure 6. The sensor elevations were 3.05, 6.1, 9.14, 12.2, and 15.24 m (10, 20, 30, 40, and 50 ft). The data were displayed in real time on a cathode-ray tube in the project control room and recorded on magnetic tape in the control tower.

Crosswind Approach and Landing Technique

The basic principles of a crosswind-landing-gear operation are illustrated in figure 10. During the approach, the airplane was crabbed into the wind, so that its ground track was along the extended runway center line with aerodynamic controls essentially neutral. With a crosswind gear, the landing gear could be aligned with the airplane ground track for touchdown. This eliminated the demanding pilot tasks and large control inputs necessary to decrab or slip the airplane prior to touchdown.

The slip, crab, and cross-runway crosswind landing techniques were investigated and reported in reference 1 for the airplane equipped with a conventional, tricycle landing gear. In the present program, the crabbed approach was used throughout, and the variables under investigation were the use of rudder pedal steering; the use of wing-lift spoilers; and the choice of either preset, automatic, or castor mode of crosswind landing gear used for alignment with the runway center line (table I).

Test Procedures

A total of 195 crosswind landings were made in this program by three test pilots who used the three modes of crosswind-landing-gear operation. Table II contains a matrix of the test conditions grouped according to crosswind magnitude, approach angle, and crosswind-landing-gear mode of operation.

Typically, the glide slope was intercepted at an altitude of 183 m (600 ft) for the 3° approaches and of 366 m (1200 ft) for the 6° approaches. The airplane was then stabilized on the approach path at an indicated speed of 65 to 75 knots with full flaps. The airplane was flared at about an altitude of 4.6 m (15 ft) for a touchdown as close as possible to the target touchdown point. The pilot's task then was to roll-out and stop the airplane within the STOL runway markings that were painted on the existing runways.

All landings were made on a dry runway in daylight with VFR conditions. After touchdown, the throttles were placed in the reverse-thrust position, but the engine response was too slow to produce appreciable reverse thrust during the ground roll-out. Little, if any, main-gear braking was used. The nose gear was steered either through the rudder pedals or the steering tiller. Wing-lift spoilers were used after touchdown for most of the landings.

RESULTS AND DISCUSSION

Data Presentation

A substantial portion of the data in this paper is presented in the form of histograms. The data given for each interval include values equal to the lower limit but exclude those equal to the upper limit. The data were sorted into the number of samples per interval, or, for control usage, into the amount of time during which the control deflections were within an interval. In most instances, the data for each interval were normalized to produce relative frequency or relative time either by dividing by the total number of samples or dividing by the total amount of time, respectively. This is the same data presentation scheme used for the data in reference 1. The actual test data from the 195 landings are also given in table III.

Although there is no single value of wind reading which completely represents the winds during an approach and landing, in order to have a consistent reference a single value was used to compute the crosswind for classifying the data for each run. This single value was that wind measured on the wind-sensor tower at the time of touchdown at the 6.1-m (20-ft) elevation (approximate airplane flare height). The summary of wind conditions for all the tests is given in figure 11 in histogram form.

Comparison of Landing-Gear Modes of Operation

With the crosswind gear, the pilots stated, ". . . it is possible to make crosswind landings in crosswind conditions that are far more severe than could be handled with the conventional gear." With the conventional gear (ref. 1) the crosswind magnitude limits were 15 to 20 knots. The largest crosswind magnitude encountered during that program was 22 knots, which caused the pilot to abort the landing just prior to touchdown. It can be seen in table II that, with the crosswind gear, 11 landings were made with crosswind magnitudes between 20 and 25 knots, and 5 landings were made with crosswind magnitudes between 25 and 30 knots. (The crosswind magnitudes of 26 to 27 knots are about one-half the stall speed of the airplane.)

The self-aligning feature of the crosswind landing gear (castor mode or automatic mode) was found to be essential for landings in severe crosswinds. For the airplane landing-gear configuration tested, the preferred mode of crosswind-landing-gear operations was the castor mode. The pilots found the crosswind landing gear to be particularly beneficial in crosswinds above 15 knots where the crab angle approached 20°. As can be seen in table II, the landings with the largest crosswinds were made with the castor mode. Continuous time histories of the sideslip angle, bank angle, total aileron deflection, crab angle, main-gear angle, nose-gear angle, and rudder deflection are given in figure 12 for three typical crosswind approaches. The wind velocity and wind direction measured on the wind-sensor tower at 1-sec intervals for several seconds near the times of touchdown are also given for each landing. Time histories from a castor-mode landing with a crosswind of 27.3 knots from the left are given in figure 12(c). During the approach and landing, the sideslip oscillated about zero until the airplane was nearly stopped on the ground; at

that time the forward speed was so low the sideslip record was off scale. Bank angle, aileron deflection, and rudder deflection also oscillated about zero. At touchdown, the main and nose gear freely aligned with the direction of travel in about 1 sec, swiveling to the right (clockwise) to offset the left crab angle. The main-gear castor locks were applied 2 sec after touchdown, and the pilot used tiller-bar steering of the nose gear. Although the pilots generally preferred rudder-pedal steering, this time the pilot felt it was necessary to use the tiller bar for steering in order to get additional nose-wheel travel. (Differential rudder-pedal steering was limited from -3° to 3°.) At the end of the ground roll, the center switch was used to bring all gear back to the airplane center line. Because of the self-aligning feature of the landing gear at touchdown, the pilot did not have to monitor or operate the gear during the approach. As one pilot said of castor-mode landings, "No precision is involved. I like them."

The pilots' second preference was for the automatic mode, saying, "[The automatic mode] should be equally as good as the castor mode if we had a higher response rate in the gear." This comment is reasonable when one considers that the automatic mode is actively self-aligning in that it requires no pilot adjustment. The automatic mode was limited somewhat by the inadequate compass-system response rate in turbulent conditions. The compass lag led to some misalignment between the gear and the airplane heading during a few landings. Time histories for an automatic-mode landing with a right crosswind of 13.6 knots are given in figure 12(b). During the approach, the main and nose gears tracked the crab angle closely through some rather severe heading changes, with the gear offset to the left (counterclockwise) to compensate for the right crab angle. At touchdown, the castor locks were applied automatically so that the landing gear stopped tracking crab angle. In this landing the pilot used rudder-pedal steering of the nose gear for about 13 sec. Note the small differential nose-gear variations (from -3° to 3°) associated with the large rudder-pedal inputs. The records were terminated before the gears were centered. If the touchdown forces on the wheels are adequate to align the gear quickly without producing an objectionable reaction in the airplane (as is true for this airplane and landing-gear configuration), the castor mode would be preferable to the more complex and expensive automatic mode.

For the preset mode, the pilot is required to set the crosswind landing gear to an appropriate offset angle at some time prior to touchdown. Time histories for a preset-mode crosswind landing with a left crosswind of 15.6 knots are given in figure 12(a). Early in the approach, the pilot selected a main-gear offset angle of 12° right to match the average left airplane crab angle. During the approach, the pilot made several adjustments, eventually returning the crosswind landing gear to 12°, after which the castor locks were applied. During the flare, a sudden change in heading due to wind shear occurred, and the airplane touched down with a 5.5° crab angle which gave a 6.5° misalignment with direction of travel. Following touchdown, the crab angle started increasing again; therefore, during the ground roll-out, the pilot used rudder-pedal steering to compensate with the full 3° nose-wheel travel available in that direction through the rudder-pedal system. This approach illustrates the problem of coordinating crab angle and gear offset angle, especially in unsteady conditions when the crab angle is continually changing. This problem is particularly severe in the flare. One of the pilots said, "In the flare, the

pilot can't be looking at the cockpit instruments, so he finds it difficult to judge if the airplane crab angle is the same (i.e., same in magnitude, but opposite in direction) as the gear angle."

The large crosswinds encountered in this program were always accompanied by considerable turbulence, gustiness, and wind shear. These unsteady conditions can be seen in the wind records in figure 12 and are also reflected in the time histories of aileron deflection, rudder deflection, and crab angle for all three approaches. It is doubtful if the pilots would have attempted a preset-mode crosswind landing in the unsteady conditions experienced during the castor-mode approach (fig. 12(c)) and the automatic-mode approach (fig. 12(b)). The castor and automatic modes relieved the pilots of continually adjusting and monitoring the landing-gear position. They found the preset mode to be very undesirable in unsteady conditions since frequent adjustments were required during the landing approach and flare. When the crosswind magnitudes were greater than 15 to 20 knots, the pilots would not attempt landings with the landing gear preset prior to touchdown. In fact, they stated that, "[The preset mode was the] most undesirable of the three modes."

Landing Data

Effect of wing-lift spoilers.- After only a few landings had been made, it was obvious that the wing-lift spoilers were relatively ineffective in destroying wing lift and increasing the wheel loads. The spoilers were located in the area of the wing covered by the propeller slipstream. (See fig. 1.) When the propellers went to flat pitch with the application of reverse thrust, the lift on that part of the wing affected by the spoilers was already destroyed, with only a small increment contributed by the spoilers. However, the pilots continued to use the wing-lift spoilers for most landings, but no attempt was made to quantify their effectiveness.

Pitch attitude at touchdown.- In figure 13, the touchdown pitch-attitude data, combined for all variables, are shown as a histogram for relative frequency of occurrence. For comparison, the combined pitch-attitude data for the conventional, tricycle landing gear from reference 1 are also included. The mean value of pitch attitude for the landings with the crosswind landing gear (1°) is 2.8° less than the mean value for the previous tests. In the unmodified airplane, the touchdown pitch attitude ranged from -4° to 12°, but in the current tests, the touchdown pitch attitude ranged from -6° to 8°.

The higher crosswinds encountered in this program were accompanied by high turbulence levels. In order to compensate, the pilots sometimes used higher stall-speed margins in the approach. These higher speeds would tend to produce the lower touchdown pitch attitudes found with the crosswind landing gear.

One pilot also felt that the lower pitch attitudes were partially caused by the need to rotate down onto the nose wheel soon after touchdown in order to use nose-wheel steering. Obviously, shallower touchdown pitch attitudes would allow faster nose-down rotations onto the nose wheel. A reduction in maximum

tail-down angle with the crosswind landing gear (8.5° compared with 10.5°) may have had some influence on the touchdown pitch attitude chosen by the pilots.

Airspeed at touchdown.- A decrease in pitch attitude would be expected to produce a corresponding increase in touchdown speed. In figure 14 it can be seen that this was not true. The ratios of airspeed at touchdown to the stall speed have been combined from all the landings with the crosswind landing gear and are presented as a histogram showing relative frequency of occurrence. The combined data from reference 1 are also included. The distribution of touchdown speed ratios is nearly the same as that of the previous tests with the conventional, tricycle landing gear. Nearly 90 percent of the landings with the crosswind landing gear were made at or above the stall speed ($V_{td}/V_{SO} \approx 1.0$), with the mean value of 1.07 as compared with a value of 1.08 for the previous tests.

Roll attitude at touchdown.- The data for roll attitude at touchdown, combined for all crosswinds, pilots, modes of crosswind-landing-gear operation, and both approach angles, are presented in figure 15 as a histogram of relative frequency of occurrence. The roll-attitude data for crab-technique landings with the conventional, tricycle landing gear from reference 1 are also shown. The roll attitude has been multiplied by the sign of the crosswind, so that landing with the wing down into the wind is a positive value, and a landing with the wing up into the wind is a negative value. The roll attitudes at touchdown with the crosswind landing gear are quite similar to the roll attitudes with the conventional, tricycle landing gear for the crab-technique landings. In both programs the mean roll attitude was 1.8°, with about 35 percent of the landings made with the wings level. In reference 1 the cross-runway technique resulted in a large number of wings-level landings because the airplane was headed closer to the relative wind. The results should have been similar for the present tests. However, a large increase in the number of wings-level landings was not experienced with the crosswind landing gear because of the turbulent and shifting wind conditions and high crosswinds; these conditions sometimes required the pilots to put a wing down into the wind to keep the airplane from drifting across the runway during the flare.

Main-gear angle and airplane crab angle at touchdown.- The purpose of the crosswind-landing-gear system was to permit the pilot to land the airplane in a crabbed attitude with the landing gear aligned with the runway center line. The potential for the largest misalignments between crab angle and main-gear angle existed for the preset mode, since the pilot had to set the landing gear while still at some altitude prior to touchdown and mentally compensate for wind shear and gusts. A comparison of main-gear angle and airplane crab angle at touchdown for the preset-mode landings is given in figure 16. The data have been combined for all pilots, all crosswinds, and both approach angles. In every preset-mode landing, the main-gear angle was larger than the airplane crab angle at touchdown, with differences ranging from 0.5° to 5.5°. The angles differed because the crab angle usually decreased slightly in the flare due to wind shear, whereas the main-gear angle was set and locked earlier in the approach in different wind conditions. Even for the preset mode, however, the landing-gear misalignment was small. In fact, there were no larger values of misalignment for any of the three modes of crosswind-landing-gear operation because the pilots chose not to use the preset mode when the crosswind was

large and variable. Under these conditions, the pilots could not estimate the amount of crab (or main-gear angle) that would be needed at touchdown. The same limitations also were exercised by the pilots regarding the automatic mode, because the system performance limitations (sticking and lag) led to excessive values of misalignment at touchdown.

The castor mode, however, allowed the pilots to operate in high crosswinds and turbulence, since the landing gears aligned themselves at touchdown through ground forces with no pilot input and no dependence on the airplane compass system, that is, a passive self-alignment system. The breakout forces on the main and nose gears were low enough that the pilots felt very little effect of the alignment forces in the castor-mode landings. The castor mode was preferred by all three pilots for its simplicity and versatility.

The airplane crab angle at touchdown is presented in figure 17 as a histogram showing relative frequency of occurrence. (The data have been combined for all pilots, all crosswinds, all modes of crosswind-landing-gear operation, and both approach angles.) The mean crab angle was 9.53°, with some values as high as 35°. The landings with high crab angles (high crosswinds) were made with the castor mode; all landings with crosswind magnitudes above 20 knots were in the castor mode. (See table II.)

Lateral acceleration at touchdown.- The lateral acceleration should be zero if the crosswind-landing-gear system is aligned with the runway center line, and if there is no drift or bank angle. Therefore, lateral acceleration at touchdown can be used as a measure of any or all of the following conditions: gear misalignment, bank angle, and aircraft drift at touchdown. Figure 18 presents the magnitude of lateral acceleration as a function of mode of landing-gear operation in terms of histograms of relative frequency of occurrence for all pilots and crosswinds and both approach angles. The mean lateral accelerations for all three modes were nearly equal; the highest magnitudes occurred during the castor-mode landings. The lateral accelerations for the automatic- and preset-mode landings were not higher because the pilots limited the use of these modes to lower crosswinds where the probabilities of misalignment and drift were relatively small. The castor mode, however, was used in all crosswind conditions. Even in the severe wind conditions experienced with the castor mode, only three runs (2.5 percent) had lateral accelerations above 0.6g, and in each of these the crosswind magnitude exceeded 15 knots.

Although the data do not reflect it, the pilots said the lateral accelerations felt lower in the castor-mode landings, which made these landings feel more comfortable. The lateral accelerations also did not cause any unusual wear on the tires, even in the castor mode where the gears were required to snap around from airplane center line in a very short time. The only excessive tire wear was produced by hard main-gear braking.

Touchdown dispersion.- The longitudinal and lateral touchdown dispersion data are shown in figures 19 and 20, respectively. The data were grouped together because there were no appreciable differences between pilots, modes of operation, or approach angles. Too few runs were made to establish definite trends with crosswind magnitude. The spread in longitudinal touchdown dispersion is very similar to the spread in the dispersion data for the crab and slip

landings with the conventional gear (ref. 1). With the crosswind landing gear, the pilots never landed shorter than the STOL strip, and they landed beyond the target touchdown zone only 23.8 percent of the time. However, the mean value for landings with the crosswind landing gear, 33.3 m (109.4 ft) beyond the target touchdown point, was about twice the mean value for the crab and slip landings reported in reference 1 for the conventional landing gear. The pilots attribute this difference to the airplane operating in higher crosswinds, and higher attendant turbulence, in the crosswind-landing-gear tests. The more severe wind conditions forced the pilots to use larger stall-speed margins during the approach; these stall-speed margins caused a tendency for the airplane to float beyond the target touchdown point. In the tests reported in reference 1, the runway markings consisted of painted squares 30.5 m (100 ft) on a side. The difference between the previous runway markings and the STOL-strip markings used in these tests also may have had some effect.

The lateral touchdown dispersion data are given in histogram form in figure 20; the data have been combined for both approach angles, all crosswinds, all pilots, and all modes of crosswind-landing-gear operation. For comparison, the combined data for the crab-technique landings with the conventional, tricycle landing gear (from ref. 1) are also shown. The data from the two landing-gear systems are quite similar. When using the crab technique with the conventional gear, the mean lateral offset was 0.1 m (0.33 ft) upwind of runway center line (a positive value), whereas with the crosswind landing gear, the mean lateral offset was 0.3 m (0.9 ft) downwind of the center line (a negative value). The majority of landings were made within ±1.5 m (±5 ft) of the center line - 83 percent of the landings with the conventional landing gear and 60 percent with the crosswind landing gear. On the other hand, the extreme values were less with the crosswind landing gear (±7.6 m (±25 ft) compared with ±10.7 m (±35 ft)). This fact is significant since the landings with the crosswind landing gear were made in higher crosswinds and greater turbulence than those with the conventional, tricycle landing gear. The crosswind landing gear permitted the pilots to crab the airplane into the wind, with no decrab or slip maneuver required for touchdown; therefore, landings were possible in higher crosswinds with less drift across the runway than with the unmodified airplane.

<u>Maximum lateral dispersion during ground roll-out</u>.- The maximum lateral dispersion from the runway center line during the ground roll-out was measured as well as the lateral touchdown dispersion. The maximum lateral dispersion during ground roll-out is defined as the maximum lateral offset of the airplane center of gravity from the runway center line during the time between touchdown and when the airplane comes to a stop. If the maximum offset occurred at touchdown, that value of offset was used as the maximum lateral dispersion for that landing. The maximum lateral dispersion data are presented in figure 21 for each crosswind-landing-gear mode of operation. The data in figure 21 have been combined for all three pilots, all crosswinds, and both approach angles. For all modes of crosswind-landing-gear operation, the maximum lateral dispersion exceeded the simulated STOL-strip edges (upwind for the automatic and castor modes and downwind for the preset mode). It is not known how much these results are influenced by the simulation of the STOL-strip edges by lines painted on wider paved runways (i.e., no penalty for crossing the edge).

In none of the landings did the dispersion exceed the paved runway limits. However, the data indicate that a runway width of ±15.24 m (±50 ft) is too narrow for high crosswind landings with the existing crosswind-landing-gear system; a more representative minimum runway width would be ±30.5 m (±100 ft), the maximum paved runway width used in these tests. This conclusion is in agreement with the results of reference 1.

Relatively few preset-mode landings were attempted, and those were limited to the lower crosswinds in relatively smooth air. In contrast, the castor-mode landings were made in the most extreme crosswinds and turbulence with dispersion performance that was essentially the same as with the preset mode. The automatic-mode landings would be expected to produce roll-out data similar to the data for castor-mode landings. However, the limitations of the airplane compass system degraded lateral roll-out performance, especially when there were sharp gusts just prior to touchdown. The compass system responded too slowly in highly turbulent conditions to align the landing gears completely; this led to some misalignment at touchdown and higher lateral dispersions during ground roll-out.

Ground-roll distance.- Ground-roll distance is the longitudinal runway distance from the point of touchdown to the point where the airplane stops. Ground-roll distance is presented for each crosswind-landing-gear mode of operation in figure 22. The data have been combined for all three pilots, all crosswinds, and both approach angles. There was no consistent attempt to stop the airplane in the shortest distance possible; however, the pilots did attempt to stop the airplane within the painted outlines of the STOL strips. The pilots could not stop the modified airplane with the crosswind landing gear in as short a distance as they could the unmodified airplane with the conventional, tricycle landing gear. The mean ground-roll distance ranged from 140 m (458 ft) to 147 m (481 ft) with the unmodified airplane (ref. 1) and from 280 m (919 ft) to 301 m (987 ft) with the modified airplane. The ground roll-outs were longer because the pilots could not utilize the full braking capability of the modified airplane system. The pilots rarely used the brakes because of the tendency to flatten one or more of the main-gear tires. One pilot, however, had consistently smaller roll distances because he was able to apply brakes lightly near the end of the ground roll-out without affecting the tires. In addition to the tire problem, another pilot used the brakes less than the other two pilots because he felt that hard braking led to unacceptable passenger ride quality.

One pilot said that even if the airplane had a more effective braking system, it could not have been used with the larger crosswinds and crab angles. At large crab angles, braking forces tend to tip the airplane forward about the horizontal axis between the nose gear and the leading main gear. For sufficiently large crab angles and forces, the tipping moments could overturn the airplane. Even with the smaller crab angles and forces, the tipping motion was quite unpleasant and would sometimes lead the pilots to back off on braking. Thus, the tipping problem could reduce the utility of increased main-gear braking authority and lead to a tendency for longer ground roll-outs for higher crosswinds.

No combined touchdown and ground roll-out exceeded the longitudinal boundaries of the simulated STOL strips, although a number of ground roll-outs ended near the end line. In an emergency, the airplane could have been stopped in a distance well short of the end line, but this would have led to very heavy tire wear.

Control Use

Control of aileron and rudder deflection and control of crab angle for the five landings with crosswind magnitudes of 25 to 30 knots were computed with the technique of reference 1. As indicated in table II, the five landings analyzed used the castor mode. Two of the landings were made with left crosswinds; three landings were made with right crosswinds. The results of the analysis for the approach, flare, and ground roll-out of the five landings are given in figure 23, which presents aileron and rudder deflection and crab angle as histograms of the relative time the values were within particular intervals.

During the approach phase of the landings (fig. 23(a)), the aileron and rudder deflections were clustered about the neutral datum, as would be expected, since the nose of the airplane was nearly aligned with the relative wind in a crabbed approach. With the right crosswinds, the rudder was within 2° or against the left stop only 0.3 percent of the time. There was adequate control for the approach phase of crosswind landings with crosswind magnitudes of 25 to 30 knots.

If figure 23(a) is compared with figure 23(b), it can be seen that larger control deflections were required in the flare phase than in the approach phase. The pilots increased their efforts for precision of flight-path control in the flare. The ailerons were used to keep the upwind wing from lifting and to counteract any tendency for the airplane to drift across the runway. The rudder was used in coordination with the ailerons to offset yaw and side forces on the airplane. The use of aileron and rudder is quite similar to that for the flares from crabbed approaches with crosswind magnitudes of 15 to 20 knots for the conventional, tricycle landing gear (ref. 1). The principal difference is that the rudder hit both control stops at the crosswind limits of 15 to 20 knots with the conventional, tricycle landing gear; but with the crosswind landing gear, the rudder hit only the left control stop in crosswinds 10 knots greater (25 to 30 knots).

During the ground roll-out (fig. 23(c)), large aileron control inputs were required for much less time with the crosswind landing gear than with the conventional, tricycle landing gear. The rudder data are not comparable since some of the rudder usage was related to ground control of nose-wheel steering rather than to aerodynamic control (for example, fig. 12(a)).

The control of aileron and rudder shown in figure 23 was quite similar to the control for the crab landings with the conventional, tricycle landing gear at crosswinds 10 knots less. The crosswind landing gear allowed the airplane to land in a crabbed attitude so that the aerodynamic limits were not reached until 25 to 30 knots, the crosswind magnitudes at which the crosswind landing gear rotated to its full physical limits. The pilots believed that it might be

possible to extend the crosswind limits to higher values by incorporating the changes outlined in the next section.

Suggestions for Further Increasing the Crosswind Landing Limits

All three pilots believed that improved crosswind landing performance, in terms of minimizing lateral dispersions and ground roll-out distance and increasing the crosswind landing limits, could be achieved if further improvements were made to the experimental crosswind-landing-gear system. Improved rudder-pedal steering capability to the nose gear would permit the pilots to steer the airplane more precisely in strong crosswind conditions. In the present crosswind-landing-gear configuration, rudder-pedal steering of the nose gear was only effective from -3° to 3° about the setting at time of actuation. The pilots found that this degree of nose-wheel travel was inadequate, so that they were forced to use asymmetric main-gear braking or tiller-bar steering of the nose gear. The pilots felt that the rudder-pedal steering capability should be at least doubled to 6° in either direction with no lag in steering response.

An equally important modification recommended by the pilots was to modify the main-gear braking and tire system to increase the braking system capability to at least that of the unmodified, production airplane. An improved braking system would permit improved directional control and shorter ground roll, although at large crab angles the usable brake capability may be limited by an airplane tip-over tendency.

Wing-lift spoilers were installed to augment the crosswind-landing-gear system by destroying wing lift and increasing the wheel loads. This spoiler installation, however, was found to be relatively ineffective because of the spoiler location on the wing. The pilots suggested that for an operational crosswind-landing-gear system, the spoilers should be located further outboard on the wings, clear of the propeller slipstream. In addition, they thought that a faster flap retraction cycle would be beneficial during the ground roll-out to further reduce wing lift. The pilots also thought that improved engine response would assist in terms of reversing thrust and improving steering (asymmetric thrust).

Overall, the pilots feel that greatly improved safety, comfort, and extended crosswind landing limits can be realized by use of an operational castor-mode crosswind-landing-gear system incorporating castor locks and rudder-pedal steering. Side forces could be reduced at touchdown to produce a smooth landing for the passengers. The operation of a crosswind landing gear on slippery runways needs further study, analysis, and testing. The application of antiskid braking systems also needs further study because of the variations in vertical load on the landing gear in strong crosswind conditions.

SUMMARY OF RESULTS

NASA has undertaken a flight research program to investigate the problems associated with landing a light, STOL transport in crosswind conditions by

using a research-type crosswind landing gear. The conclusions reached in this study are for this particular type of airplane and research-type crosswind-landing-gear system. This study indicated the following results:

1. The crosswind landing gear permitted the pilots to crab the airplane into the wind, with no decrab or slip maneuver required for touchdown; therefore, landings were possible in higher crosswinds with less drift across the runway than were possible with the unmodified airplane with the crosswind landing gear. Crosswind landings were made with crosswind magnitudes of 25 to 30 knots, whereas the crosswind magnitude limits with the conventional, tricycle landing gear were 15 to 20 knots.

2. For the light transport used in this investigation, the self-aligning feature of the crosswind landing gear (either automatic or castor mode) was found to be essential for landing in severe crosswinds.

3. If, as with the airplane and landing-gear configuration tested, the touchdown forces on the wheels are adequate to align the gear quickly without producing an objectionable reaction in the airplane, the castor mode is preferable to the more complex and expensive automatic-mode landing gear.

4. Because of the difficulty in coordinating crab angle and gear preset angle, the pilots would not attempt preset-mode landings when the crosswind magnitudes were greater than 15 to 20 knots.

5. The data indicate that a runway width of ±15.24 m (±50 ft) is too narrow for high crosswind landings with the existing crosswind-landing-gear system; a more representative minimum runway width would be ±30.5 m (±100 ft), the maximum paved runway width used in these tests.

Langley Research Center
National Aeronautics and Space Administration
Hampton, VA 23665
March 30, 1979

REFERENCES

1. Fisher, Bruce D.; Champine, Robert A.; Deal, Perry L.; Patton, James M., Jr.; and Hall, Albert W.: A Flight Investigation of Piloting Techniques and Crosswind Limitations During Visual STOL-Type Landing Operations. NASA TN D-8284, 1976.

2. Stubbs, Sandy M.; Byrdsong, Thomas A.; and Sleeper, Robert K.: An Experimental Simulation Study of Four Crosswind Landing-Gear Concepts. NASA TN D-7864, 1975.

3. Fisher, Bruce D.; Sleeper, Robert K.; and Stubbs, Sandy M.: Summary of NASA Landing Gear Research. NASA TM-78679, 1978.

4. Standard for Metric Practice. E 380-76, American Soc. Testing & Mater., 1976.

5. Champine, Robert A.: Crosswind Landing-Gear Position Indicator. NASA Tech Brief LAR-11941, 1976.

6. Spangler, Roman M., Jr.: Simulated Ground-Level STOL Runway/Aircraft Evaluation. FAA-RD-73-110, Sept. 1973.

TABLE I.- MODES OF LANDING-GEAR OPERATION FOR CROSSWIND RESEARCH

Mode	Crab set of gear	Ground control for all modes
Preset	Pilot control during approach	In addition to conventional aerodynamic, brake, and low-speed nose-wheel steering control, the pilot can select any of the following controls: (1) Castor lock of the main landing gear (2) Nose-wheel steering at high speed through rudder pedals (3) Wing-lift spoilers (4) Return gear to center
Automatic	Servo driven by signals from airplane heading and runway direction	
Castor	Passive - by ground forces during touchdown	

TABLE II.- MATRIX OF TEST CONDITIONS RECORDED FOR 195 LANDINGS

Approach angle, deg	Number of landings for crosswind magnitude intervals of -						Crosswind-landing-gear mode
	0 to 5 knots	5 to 10 knots	10 to 15 knots	15 to 20 knots	20 to 25 knots	25 to 30 knots	
-3	0	11	11	4	0	0	Preset
-3	0	17	20	5	0	0	Automatic
-3	4	20	37	45	11	5	Castor
-6	0	0	0	0	0	0	Preset
-6	0	1	0	0	0	0	Automatic
-6	1	3	0	0	0	0	Castor

TABLE III.- TEST DATA FROM 195 LANDINGS

Run	Crosswind-landing-gear mode	Pilot	Approach angle, deg	Spoilers	Crosswind, knots (a)	Wind component parallel to runway, knots (b)	Longitudinal touchdown dispersion (c), m	Longitudinal touchdown dispersion (c), ft	Lateral touchdown dispersion (d), m	Lateral touchdown dispersion (d), ft	Maximum lateral dispersion (e), m	Maximum lateral dispersion (e), ft	Ground-roll distance, m	Ground-roll distance, ft	θ_{td}, deg	V_{td}/V_{SO}	ϕ_{td}, deg	$\delta_{mg,td}$, deg	$\delta_{crab,td}$, deg	$a_{y,td}$, g units
1	Automatic	A	-3	Up	-9.7	-4.0	22.9	75	0	0	-4.1	-13.3	221.0	725	-3	1.23	-2	-1	-----	-0.33
2	Automatic	A	-3	Up	-8.5	-3.7	45.7	150	1.1	3.5	-13.9	-45.5	259.1	850	-2.5	1.02	-1	3	-----	-.15
3	Automatic	A	-3	Up	-9.6	3.6	30.5	100	0	0	-2.0	-6.5	213.4	700	-2.5	1.14	-1	3	-----	-.25
4	Automatic	A	-3	Up	-7.9	.9	38.1	125	0	0	-5.0	-16.3	205.7	675	-2	1.03	-.5	-1	-----	-.15
5	Automatic	A	-3	Up	9.3	5.3	-3.0	-10	-1.1	-3.5	-4.6	-15.2	271.3	890	-2.5	1.09	1.5	-4.5	-2.5	-.11
6	Automatic	A	-3	Up	6.7	4.1	38.1	125	-1.0	-3.3	-3.1	-10.2	266.7	875	-3	1.11	.5	-7.5	-5.5	-.1
7	Automatic	A	-3	Up	6.6	5.9	30.5	100	-2.0	-6.6	-9.1	-30	335.3	1100	-1.5	1.00	0	-10	-8.5	-.19
8	Automatic	A	-3	Up	6.6	7.7	27.4	90	-1.0	-3.3	-4.3	-14	277.4	910	-2	1.05	0	-6.5	-6.5	.18
9	Automatic	A	-3	Up	7.1	5.0	15.2	50	-.5	-1.7	-2.9	-9.6	320.0	1050	-3	1.1	-.5	-4.5	-3.5	-.13
10	Automatic	A	-3	Up	12.4	3.7	48.8	160	0	0	-1.9	-6.4	286.5	940	-1.5	1.14	.3	-8.5	-7	-.1
11	Automatic	A	-3	Up	11.5	.8	15.2	50	1.0	3.4	-3.7	-12.3	228.6	750	1.5	1.09	-5	-13	-7.5	-.22
12	Automatic	A	-3	Up	9.5	-.2	33.5	110	0	0	-4.9	-16	301.8	990	-2.5	1.1	0	-12	-9.5	-.1
13	Castor	A	-3	Up	6.5	5	91.4	300	-2.5	-8.3	-5.5	-18	274.3	900	-1	1.03	-.5	-4	-----	.15
14	Castor	A	-3	Up	9.2	3.5	27.4	90	-1.0	-3.3	-1.9	-6.4	307.8	1010	1	1.03	.5	-2	-8	.2
15	Castor	A	-3	Up	8.8	3	-30.5	-100	-2.3	-7.4	-2.7	-8.8	335.3	1100	.5	.98	.5	-2.5	-9.5	.15
16	Castor	A	-3	Up	7.7	4.8	15.2	50	-1.0	-3.4	-3.4	-11.2	320.0	1050	-1	1.04	1.0	-3	-8.5	.21
17	Castor	A	-3	Up	4.9	3.6	27.4	90	-2.0	-6.6	-2.0	-6.6	307.8	1010	-1.5	1.04	0	-1	-3	.13
18	Castor	A	-3	Up	12.5	3	-15.2	-50	1.1	3.7	-3.4	-11.2	350.5	1150	-1	1.04	-.5	-8.5	-2	.2
19	Castor	A	-3	Up	16.7	4.1	-6.1	-20	0	0	-5.3	-17.5	310.9	1020	-1	1.09	1.5	-8.5	-8	.25
20	Castor	A	-3	Up	13.9	-2.2	-1.5	-5	1.1	3.5	-3.2	-10.5	367.3	1205	-2	1.09	0	-1	-3	.2
21	Preset	A	-3	Up	-9.7	5	137.2	450	-2.1	-7	-8.5	-28	-----	----	-2.0	1.02	0	-2	-----	-.43
22	Preset	A	-3	Up	-8.8	.5	68.6	225	-1.1	-3.5	-8.8	-29	281.9	925	-.5	1.17	0	-3	-----	-.35
23	Preset	A	-3	Up	-8.3	-5.4	30.5	100	1.1	3.5	-6.3	-20.7	243.8	800	-1.5	1.08	1	-3	-----	-.2
24	Preset	A	-3	Up	8.5	4.8	-22.9	-75	-3.3	-10.9	-22.9	-75	281.9	925	-1	1.00	1	-11.5	-9.5	-.28
25	Preset	A	-3	Up	10.3	2.1	-15.2	-50	-2.2	-7.2	-5.3	-17.5	289.6	950	-2	1.05	1	-7.5	-4.5	±.1
26	Preset	A	-3	Up	12.3	-2.1	36.6	120	-2.0	-6.5	-7.6	-25	359.7	1180	-3	1.08	0	-14.5	-12.5	-.14
27	Preset	A	-3	Up	15.1	-1.0	0	0	0	0	-18.3	-60	304.8	1000	-.5	1.00	0	-18	-12.5	-.5
28	Preset	A	-3	Up	13.5	6.1	3.0	10	2.1	7	-9.1	-30	347.5	1140	-4	1.08	1	-16	-11	-.2
29	Automatic	B	-3	Up	6.1	-2.6	97.5	320	-2.1	-7	-5.4	-17.9	298.7	980	1	1.09	1.5	-7	-----	-.19
30	Automatic	B	-3	Down	13.9	-1.8	30.5	100	-1.0	-3.3	-3.8	-12.5	396.2	1300	3.5	1.01	0	-17.5	-13.5	-.14
31	Automatic	B	-3	Down	18.1	6.2	45.7	150	-1.0	-3.2	-4.9	-16	289.6	950	4	.97	.5	-20	-19.5	-.15
32	Automatic	B	-3	Down	13.5	5.6	70.1	230	-.9	-3	1.0	3.2	265.2	870	1	1.02	-1	-17.5	-18.5	-.08
33	Automatic	B	-3	Down	14.8	6.9	121.9	400	1.7	5.5	-6.8	-22.4	259.1	850	2.5	1.02	3.5	-20.5	-19	-.11
34	Automatic	B	-3	Up	13.6	5.4	91.4	300	.9	2.9	-7.7	-25.2	289.6	950	-3	1.08	1	-19.5	-17.5	-.15
35	Automatic	B	-3	Up	-12.4	5.1	61.0	200	.9	3.1	2.6	8.7	298.7	980	4	.95	-3	7.5	8.5	-.13
36	Automatic	B	-3	Up	-11	2.1	38.1	125	1.0	3.3	2.4	7.8	300.2	985	4	1.00	-3	7.5	8	-.08
37	Automatic	B	-3	Down	10.9	1.1	30.5	100	.9	3.1	2.5	8.2	198.1	650	4	1.05	3.5	-2	-.5	.14
38	Automatic	B	-3	Down	11.1	.2	45.7	150	.9	2.9	3.3	11.0	253.0	830	2	1.05	1.5	-2.5	-.5	.29

[a]Crosswind is positive for crosswind from right.
[b]Wind component parallel to runway is positive for headwind.
[c]Longitudinal touchdown dispersion is positive for landing long of touchdown point.
[d]Lateral touchdown dispersion is positive for landing to pilot's right of runway center line.
[e]Maximum lateral dispersion is positive for landing to pilot's right of runway center line.

TABLE III.- Continued

Run	Crosswind-landing-gear mode	Pilot	Approach angle, deg	Spoilers	Crosswind, knots (a)	Wind component parallel to runway, knots (b)	Longitudinal touchdown dispersion (c)		Lateral touchdown dispersion (d)		Maximum lateral dispersion (e)		Ground-roll distance		θ_{td}, deg	V_{td}/V_{SO}	ϕ_{td}, deg	$\delta_{mg,td}$, deg	$\delta_{crab,td}$, deg	$a_{y,td}$, g units
							m	ft	m	ft	m	ft	m	ft						
39	Automatic	B	-3	Up	-16.4	6.5	0	0	2.1	7	2.1	7	243.8	800	2.5	1.03	-4	10.6	9.5	-0.03
40	Automatic	B	-3	Up	-14.9	5.0	15.2	50	2.1	6.8	2.1	6.8	228.6	750	1.5	1.09	-6	8.4	10	-.12
41	Automatic	B	-3	Up	-11.9	6.7	22.9	75	----	-----	-----	-----	221.0	725	1.9	1.10	-1	11	9.3	.12
42	Castor	B	-3	Up	6.2	-5.8	167.6	550	0	0	-1.4	-4.6	289.6	950	3	1.03	3	-2	-----	.05
43	Castor	B	-3	Up	-13	-2.3	61.0	200	.9	3.1	2.0	6.5	304.8	1000	4	1.02	-3	14	4	-.18
44	Castor	B	-3	Up	-15.9	-2.4	67.0	220	.9	3.0	-6.4	-21	268.2	880	5.5	.97	-1	9	2	-.15
45	Castor	B	-3	Up	25.9	4.9	48.8	160	0	0	12.2	40	195.1	640	3	1.13	-1	-13.5	-23.5	.65
46	Castor	B	-3	Up	15	8.6	91.4	300	3.5	11.6	15.2	50	213.4	700	.5	1.14	5	-8.5	-21	.33
47	Castor	B	-3	Up	15.7	2.1	137.2	450	1.6	5.3	6.1	20	289.6	950	1	.98	0	-7	-16	.46
48	Castor	B	-3	Up	16.9	4.1	61.0	200	0	0	3.4	11.2	289.6	950	1.5	1.09	3.5	-8.5	-20	.34
49	Castor	B	-3	Up	19.4	3.4	61.0	200	0	0	2.1	7	243.8	800	2	.99	1	-8.5	-19	.12
50	Castor	B	-3	Up	10.8	2	91.4	300	.9	2.9	4.3	14	289.6	950	2	1.04	2.5	-3.5	-22	.32
51	Castor	B	-3	Up	-14.3	3.9	12.2	40	1.0	3.4	-5.7	-18.8	254.5	835	4.5	1.01	-3	9	6.5	-.18
52	Castor	B	-3	Up	-11.5	1.9	30.5	100	1.0	3.3	1.0	3.3	304.8	1000	3.8	1.01	-3	7	6.5	-.16
53	Castor	B	-3	Up	7.3	.5	6.1	20	2.1	6.9	2.1	6.9	268.2	880	5.8	.94	-1	-6	-9	.16
54	Castor	B	-3	Up	12	-.9	61.0	200	.8	2.7	3.2	10.4	274.3	900	4.5	1.04	2	-8	-14	.16
55	Castor	B	-3	Up	9.8	.4	0	0	0	0	1.7	5.6	304.8	1000	2.3	1.01	4	-8.8	-11	.19
56	Castor	B	-3	Down	14.6	1.1	30.5	100	.9	3.1	3.0	9.7	274.3	900	1.0	1.06	2.5	-3	-10	.18
57	Castor	B	-3	Up	12.2	-1.3	27.4	90	.9	3.1	1.9	6.4	231.6	760	2.0	1.10	3.0	-7	-4.5	.27
58	Castor	B	-3	Up	-9	6.4	-61.0	-200	1.4	4.5	1.4	4.5	274.3	900	2	1.03	-5.7	4	6.3	-.15
59	Castor	B	-3	Up	-5.6	5.9	-30.5	-100	2.4	7.9	2.4	7.9	243.8	800	2.5	1.05	-1	6	5.8	-.15
60	Castor	B	-3	Up	-8.2	6.5	-15.2	-50	2.3	7.4	2.3	7.4	213.4	700	3.5	1.04	-.5	5.5	5.5	-.12
61	Castor	B	-3	Up	-7.5	2.4	-61.0	-200	2.7	9	2.7	9	213.4	700	3	1.04	-1	7	9.5	-.14
62	Castor	B	-3	Up	-15.1	5.2	-15.2	-50	1.1	3.6	1.1	3.6	274.3	900	4.5	1.01	-4	7.5	3.5	-.15
63	Castor	B	-3	Up	-13.7	4.8	54.9	180	.5	1.6	1.7	5.7	219.5	720	4	1.02	-.5	9	10	-.39
64	Castor	B	-3	Up	-11.5	4.6	-6.1	-20	.5	1.8	.5	1.8	234.7	770	6	1.02	-3	12	15.5	-.31
65	Castor	B	-3	Up	-12.7	4.5	6.1	20	0	0	0	0	231.6	760	4.5	1.05	-2.5	8	6.5	-.06
66	Castor	B	-3	Up	-14.2	4.5	6.1	20	0	0	0	0	253.0	830	5	1.06	-3	8.5	5.5	-.11
67	Castor	B	-3	Up	-12.4	4.1	0	0	0	0	-1.9	-6.3	236.2	775	3.1	1.08	-2	9.5	8	-.17
68	Castor	B	-3	Up	-16.9	-.1	0	0	0	0	0	0	237.7	780	6.1	1.06	-2.8	9	13	-.23
69	Castor	B	-3	Up	-16.7	4.6	-7.6	-25	0	0	.9	2.9	221.0	725	4	1.04	-1	9.5	7.5	-.13
70	Castor	B	-3	Up	-17	8.8	22.9	75	1.0	3.4	1.0	3.4	205.7	675	1	1.04	-5	15	14	-.32
71	Castor	B	-3	Up	-14.1	4.3	-15.2	-50	1.1	3.6	1.1	3.6	213.4	700	7.6	1.05	-3	10.5	15	-.14
72	Castor	B	-3	Up	-15.8	7.4	-15.2	-50	1.1	3.6	1.1	3.6	243.8	800	6.1	1.05	-3	13	14	-.22
73	Castor	B	-3	Down	-16.1	7.4	-15.2	-50	1.1	3.6	-1.7	-5.5	259.1	850	1.8	1.1	-7.1	6	11	-.16
74	Castor	B	-3	Up	-15.2	2.3	30.5	100	1.0	3.4	1.0	3.4	213.4	700	3.8	1	-2	12	12.8	-.19
75	Castor	B	-3	Up	-16.5	1.9	15.2	50	.5	1.7	.5	1.7	228.6	750	4.9	1.01	-2	11.5	12	-.14
76	Castor	B	-3	Up	-16.4	3.9	15.2	50	1.6	5.1	1.6	5.1	228.6	750	6.8	1.06	-2	11.6	11.5	-.24
77	Castor	B	-3	Up	-16	4.9	15.2	50	0	0	0	0	228.6	750	6	1.04	-3	9	8.8	-.23
78	Castor	B	-3	Up	-17.5	4.9	76.2	250	----	-----	-----	-----	243.8	800	6.7	1.08	-1	14.9	16	-.26

[a] Crosswind is positive for crosswind from right.
[b] Wind component parallel to runway is positive for headwind.
[c] Longitudinal touchdown dispersion is positive for landing long of touchdown point.
[d] Lateral touchdown dispersion is positive for landing to pilot's right of runway center line.
[e] Maximum lateral dispersion is positive for landing to pilot's right of runway center line.

TABLE III.- Continued

Run	Crosswind-landing-gear mode	Pilot	Approach angle, deg	Spoilers	Crosswind, knots (a)	Wind component parallel to runway, knots (b)	Longitudinal touchdown dispersion (c)		Lateral touchdown dispersion (d)		Maximum lateral dispersion (e)		Ground-roll distance		θ_{td}, deg	V_{td}/V_{SO}	ϕ_{td}, deg	$\delta_{mg,td}$, deg	$\delta_{crab,td}$, deg	$a_{y,td}$, g units
							m	ft	m	ft	m	ft	m	ft						
79	Castor	B	-3	Up	-11.6	9	152.4	500	----	-----	-----	-----	167.6	550	4	1.05	-3.5	16	15	-0.23
80	Castor	B	-3	Up	-17.2	15.9	12.2	40	----	-----	-----	-----	231.6	760	6	.95	-4.5	13	16.5	-.25
81	Castor	B	-3	Up	-14.9	1	0	0	----	-----	-----	-----	274.3	900	6.9	1.05	-4	9	16.3	-.17
82	Castor	B	-3	Up	-19	2.3	-30.5	-100	----	-----	-----	-----	243.8	800	6.9	.98	-1.5	14	16	-.28
83	Castor	B	-3	Up	-10.9	6.8	-7.6	-25	----	-----	-----	-----	259.1	850	6	1.04	-4.5	12	17.5	-.23
84	Castor	B	-3	Up	-16.1	10.5	22.9	75	----	-----	-----	-----	221.0	725	3.1	1.06	0	13	12.5	.04
85	Castor	B	-3	Up	-11.5	4.6	30.5	100	----	-----	-----	-----	182.9	600	-1.5	1.11	-2	6	8.5	-.13
86	Castor	B	-3	Up	8.5	-2.2	76.2	250	.9	2.8	1.5	4.9	259.1	850	----	----	----	-----	-----	-----
87	Castor	B	-3	Up	-3.7	3.9	0	0	2.1	7	2.1	7	259.1	850	----	----	----	-----	-----	-----
88	Preset	B	-3	Down	11.8	-1.1	152.4	500	0	0	-.9	-3	358.1	1175	2.3	.94	0	-18	-----	-.15
89	Preset	B	-3	Up	13.5	-3.7	97.5	320	0	0	-1.8	-6	268.2	880	2.5	.99	1	-16	-----	-.1
90	Preset	B	-3	Up	9	-3.9	106.7	350	0	0	-1.2	-4	403.9	1325	1.0	.99	2	-16.5	-----	.05
91	Preset	B	-3	Up	7.7	-4.6	39.6	130	3.2	10.5	-4.0	-13	295.7	970	4.5	1.03	4	-4	-----	-.23
92	Preset	B	-3	Up	7.6	-3.5	76.2	250	5.3	17.5	-7.3	-24	289.6	950	-.5	1.08	0	-8	-----	-.29
93	Preset	B	-3	Up	-15.6	2.3	15.2	50	0	0	3.0	9.8	320.0	1050	4.5	.99	-1.5	11.5	5.5	.27
94	Preset	B	-3	Up	-16.6	1.9	61.0	200	.9	3.1	-1.9	-6.2	304.8	1000	4	.99	-3	8	6.5	-.21
95	Preset	B	-3	Up	-15	2.7	-24.4	-80	1.1	3.7	1.8	6	268.2	880	3.5	1.09	-3	6	.5	.05
96	Preset	B	-3	Up	-13.8	7.2	30.5	100	3.0	9.9	3.6	11.9	274.3	900	4.5	1.05	-2.8	9	8.5	-.1
97	Preset	B	-3	Up	-13.1	5.6	18.3	60	1.0	3.4	2.3	7.7	280.4	920	5	.98	-2	9.5	7	-.14
98	Preset	B	-3	Up	8.3	.3	45.7	150	.4	1.4	1.9	6.1	213.4	700	1.8	1.05	2.5	-6	-----	-.13
99	Preset	B	-3	Up	11	2.7	76.2	250	.9	2.8	3.0	10	259.1	850	1.0	1.01	1.0	-5.6	-----	.15
100	Preset	B	-3	Up	10.2	-3.2	45.7	150	.9	2.9	2.3	7.4	213.4	700	2.5	1.05	2.0	-6	-3.5	.08
101	Preset	B	-3	Up	9.1	-2.7	91.4	300	1.1	3.5	1.8	6	274.3	900	----	----	----	-----	-----	-----
102	Automatic	B	-6	Up	7.5	10.0	61.0	200	-.8	-2.7	.3	1.1	274.3	900	2	1.08	.5	-6	-4.5	-.16
103	Castor	B	-6	Up	8.4	-2.7	76.2	250	-.8	-2.6	1.6	5.3	274.3	900	3.5	.98	1.5	-3.5	-8	.11
104	Castor	B	-6	Up	2.5	3.4	83.8	275	-.8	-2.5	.2	.7	266.7	875	1.6	1.06	2.0	-5	-10	.23
105	Castor	B	-6	Up	5.1	2.2	91.4	300	0	0	.5	1.8	243.8	800	2.6	1.08	-2.3	-3	-----	.05
106	Castor	B	-6	Up	7.2	4.1	83.8	275	-.8	-2.5	.3	1.1	251.5	825	.6	1.04	-1	0	0	.1
107	Automatic	C	-3	Up	10.2	-3.8	1.5	5	-1.1	-3.5	-3.0	-9.8	364.2	1195	1.8	.99	2.5	-9.0	-9.0	-.14
108	Automatic	C	-3	Up	11.4	.7	1.5	5	1.1	3.5	-1.3	-4.4	333.8	1095	-2.0	.99	1.0	-4.5	-4.5	.18
109	Automatic	C	-3	Up	13.7	.8	-9.1	-30	1.1	3.6	-1.8	-5.8	344.4	1130	2.0	1.05	2.0	-4.0	-5.5	.18
110	Automatic	C	-3	Up	-13.1	5	-22.9	-75	4.5	14.8	-23.5	-77	342.9	1125	1.5	1.09	-2.0	-4.5	-----	-.31
111	Automatic	C	-3	Up	-15.2	10.4	61.0	200	1.6	5.4	-4.4	-14.3	304.8	1000	-2	1.07	-3.5	13	13	.14
112	Automatic	C	-3	Up	-16	12.1	15.2	50	1.0	3.3	-15.2	-50	289.6	950	-2	1.13	.5	10.5	6	.16
113	Automatic	C	-3	Down	-13.8	7	-30.5	-100	1.2	4.0	-6.2	-20.3	396.2	1300	-.3	1.01	-2	3.5	1.5	-.2
114	Automatic	C	-3	Up	-13.6	9.2	15.2	50	1.0	3.3	9.4	31	350.5	1150	-3	1.09	-2.5	2	0	-.33
115	Automatic	C	-3	Up	-16.3	2.2	15.2	50	1.0	3.3	-6.3	-20.7	350.5	1150	-4	1.10	1.0	6	4	-.29

[a] Crosswind is positive for crosswind from right.
[b] Wind component parallel to runway is positive for headwind.
[c] Longitudinal touchdown dispersion is positive for landing long of touchdown point.
[d] Lateral touchdown dispersion is positive for landing to pilot's right of runway center line.
[e] Maximum lateral dispersion is positive for landing to pilot's right of runway center line.

TABLE III.- Continued

Run	Crosswind-landing-gear mode	Pilot	Approach angle, deg	Spoilers	Crosswind, knots (a)	Wind component parallel to runway, knots (b)	Longitudinal touchdown dispersion (c)		Lateral touchdown dispersion (d)		Maximum lateral dispersion (e)		Ground-roll distance		θ_{td}, deg	V_{td}/V_{SO}	ϕ_{td}, deg	$\delta_{mg,td}$, deg	$\delta_{crab,td}$, deg	$a_{y,td}$, g units
							m	ft	m	ft	m	ft	m	ft						
116	Automatic	C	-3	Up	-8	6	0	0	2.1	7	2.1	7	365.8	1200	0	1.07	0.5	4.5	3.5	-0.14
117	Automatic	C	-3	Up	-9.3	3.8	76.2	250	1.8	6	1.8	6	289.6	950	-3.5	1.08	1.5	5.5	3	-.1
118	Automatic	C	-3	Up	-7.1	3.5	121.9	400	1.6	5.4	1.6	5.4	243.8	800	-3.5	1.13	.5	6	4	0
119	Automatic	C	-3	Up	-6.9	8	30.5	100	1.0	3.3	1.0	3.3	213.4	700	0	1.06	-1	6	5	-.11
120	Automatic	C	-3	Up	-9.2	7.3	0	0	0	0	-1.8	-6	274.3	900	1.1	1.11	-1	6.33	3.5	-.17
121	Automatic	C	-3	Up	-8.4	9.7	15.2	50	0	0	-.9	-2.9	137.2	450	-2.5	1.13	1	7.3	6.7	-.33
122	Automatic	C	-3	Up	-11.6	6.7	30.5	100	0	0	-1.6	-5.4	121.9	400	-1.5	1.13	1.3	6.5	6.5	-.46
123	Automatic	C	-3	Up	-11	8.7	0	0	1.1	3.5	1.1	3.5	152.4	500	-1	1.07	-.8	7	7	-.35
124	Castor	C	-3	Up	11.3	.3	-15.2	-50	-1.1	-3.6	2.2	7.3	350.5	1150	2	1.11	.5	-1	-3.5	-.1
125	Castor	C	-3	Up	13.1	1.2	-6.1	-20	-1.1	-3.6	-2.6	-8.4	-----	----	1.8	1.02	.5	-4	-9	.15
126	Castor	C	-3	Up	14.4	-4.2	15.2	50	-1.0	-3.4	-2.5	-8.3	388.6	1275	-.5	1.08	1.0	0	-5.5	.08
127	Castor	C	-3	Up	9.2	.3	-18.3	-60	-2.2	-7.3	-4.3	-14.0	-----	----	2.7	1.08	1.0	0	-2	-.1
128	Castor	C	-3	Up	-14.4	5.1	0	0	4.3	14.0	4.3	14	365.8	1200	0	1.09	-1.5	7.5	3.5	-.14
129	Castor	C	-3	Up	-16.8	2.5	15.2	50	4.1	13.4	-20.1	-66	259.1	850	1.4	1.03	-2	8	3	-.25
130	Castor	C	-3	Up	-15.7	4.8	-15.2	-50	4.4	14.6	4.3	14	381.0	1250	0	1.07	-2	9	1.5	-.50
131	Castor	C	-3	Up	-8.9	5.5	-----	----	----	-----	-----	-----	-----	----	0	1.14	-1.5	7.5	15.5	-.1
132	Castor	C	-3	Up	-15.7	6.2	64.0	210	.8	2.7	-3.5	-11.4	301.8	990	-6	1.16	.3	6	10.5	-.22
133	Castor	C	-3	Up	-10	9.3	61.0	200	.8	2.7	2.8	9.3	304.8	1000	-2.5	1.12	0	7	6.5	-.32
134	Castor	C	-3	Up	-17.7	7.5	6.1	20	1.6	5.1	1.6	5.1	359.7	1180	-.9	1.12	-2.5	7.6	3.0	-.21
135	Castor	C	-3	Up	-11	6.0	-7.6	-25	1.1	3.6	1.1	3.6	373.4	1225	-1.0	1.05	.5	9.5	1.0	-.18
136	Castor	C	-3	Up	-7.9	6.9	-15.2	-50	1.7	5.6	1.7	5.6	381.0	1250	-1.0	1.10	0	7.5	-1.0	±.13
137	Castor	C	-3	Up	-14.7	-4	-7.6	-25	1.1	3.6	-4.0	-13.1	373.4	1225	-.3	1.06	1.0	7	-3.5	-.25
138	Castor	C	-3	Up	15.6	2	-15.2	-50	2.3	7.4	8.0	26.4	381.0	1250	.3	1.09	3.0	-9	-13	.26
139	Castor	C	-3	Up	18.9	6.1	15.2	50	2.0	6.5	-2.6	-8.4	350.5	1150	0	1.12	4.3	-7.5	-11.5	.20
140	Castor	C	-3	Up	25.5	9	30.5	100	1.9	6.1	-5.1	-16.8	335.3	1100	0	1.08	5	.5	-4.5	.15
141	Castor	C	-3	Up	17.7	6.3	45.7	150	1.8	5.8	2.8	9.3	320.0	1050	-2.5	1.18	3	0	-8.5	.23
142	Castor	C	-3	Up	18.9	2.9	22.9	75	1.9	6.3	1.9	6.3	342.9	1125	-1	1.23	5	-2.3	-7	.10
143	Castor	C	-3	Up	18.5	1.6	22.9	75	1.9	6.3	6.6	21.7	342.9	1125	-1.5	1.13	2.5	-.5	-3.5	.08
144	Castor	C	-3	Up	19.3	8.6	15.2	50	2.0	6.5	3.7	12	350.5	1150	-1	1.14	6.5	-8.1	-5	.16
145	Castor	C	-3	Up	19.9	5.6	30.5	100	1.9	6.1	1.9	6.1	335.3	1100	-3	1.23	3.5	-4.8	-----	.14
146	Castor	C	-3	Up	23.6	4.3	30.5	100	1.9	6.1	5.7	18.6	335.3	1100	-.5	1.09	4	-4.3	-----	.13
147	Castor	C	-3	Up	22.4	3.4	6.1	20	1.0	3.4	3.6	11.9	359.7	1180	1.3	1.14	5.5	0	-----	.03
148	Castor	C	-3	Up	23.6	5	0	0	2.1	7	7.8	25.5	365.8	1200	-.5	1.14	4	-4.8	-----	.05
149	Castor	C	-3	Up	17.1	3.9	61.0	200	1.6	5.4	2.4	7.8	304.8	1000	-4	1.09	4	-4	-3.5	.2
150	Castor	C	-3	Up	17.1	7	0	0	1.1	3.5	3.6	11.9	365.8	1200	-.5	1.05	5.5	-2.9	-4.5	.16
151	Castor	C	-3	Up	18.8	7.2	30.5	100	1.9	6.1	1.9	6.1	335.3	1100	-2	1.14	4	-5.3	-----	.13
152	Castor	C	-3	Up	22.5	8.5	45.7	150	1.8	5.8	4.5	14.8	320.0	1050	-2	1.23	1.5	-5.8	-----	-.12
153	Castor	C	-3	Up	22.1	6.6	61.0	200	3.3	10.8	-7.8	-25.5	304.8	1000	-4.3	1.20	4	0	-----	.1
154	Castor	C	-3	Up	17.6	6.6	30.5	100	2.8	9.2	3.5	11.6	335.3	1100	-4	1.16	2.3	-5.5	-----	.08
155	Castor	C	-3	Up	20.2	5.9	76.2	250	1.6	5.1	-8.5	-28	289.6	950	-6	1.31	6	.5	-1.8	-.05

[a]Crosswind is positive for crosswind from right.
[b]Wind component parallel to runway is positive for headwind.
[c]Longitudinal touchdown dispersion is positive for landing long of touchdown point.
[d]Lateral touchdown dispersion is positive for landing to pilot's right of runway center line.
[e]Maximum lateral dispersion is positive for landing to pilot's right of runway center line.

TABLE III.- Concluded

Run	Crosswind-landing-gear mode	Pilot	Approach angle, deg	Spoilers	Crosswind, knots (a)	Wind component parallel to runway, knots (b)	Longitudinal touchdown dispersion (c)		Lateral touchdown dispersion (d)		Maximum lateral dispersion (e)		Ground-roll distance		θ_{td}, deg	V_{td}/V_{SO}	ϕ_{td}, deg	$\delta_{mg,td}$, deg	$\delta_{crab,td}$, deg	$a_{y,td}$, g units
							m	ft	m	ft	m	ft	m	ft						
156	Castor	C	-3	Up	24	7.2	30.5	100	2.8	9.2	8.5	27.9	335.3	1100	-2.2	1.19	4	-5	-----	-0.04
157	Castor	C	-3	Up	19.7	6.7	61.0	200	1.6	5.4	1.6	5.4	304.8	1000	-2.2	1.21	6	1	-----	.06
158	Castor	C	-3	Up	17.6	6.9	0	0	2.1	7	2.1	7	365.8	1200	-4	1.22	2.5	-2	0	.14
159	Castor	C	-3	Up	26	3.6	0	0	2.1	7	-----	-----	365.8	1200	-3	1.26	2.5	-5	1	.06
160	Castor	C	-3	Up	18.1	5.5	-----	----	----	-----	-----	-----	-----	----	-3	1.12	5	-1.5	-----	-.05
161	Castor	C	-3	Up	-3.5	6.9	0	0	2.1	7	2.1	7	304.8	1000	-.2	1.11	.5	7	7.5	-.26
162	Castor	C	-3	Up	-10.3	7.1	-15.2	-50	2.2	7.2	2.2	7.2	259.1	850	.3	1.11	.5	4.5	8	-.22
163	Castor	C	-3	Up	-6.8	2.6	61.0	200	2.8	9.3	2.8	9.3	289.6	950	-1	1.08	.3	6	6	-.17
164	Castor	C	-3	Up	-8	2.0	15.2	50	3.1	10.2	3.1	10.2	228.6	750	-1.5	1.01	-1.5	7.5	8.5	-.23
165	Castor	C	-3	Up	-6.6	6.5	61.0	200	1.9	6.2	1.9	6.2	198.1	650	-1.5	1.11	-.5	3	4	-.14
166	Castor	C	-3	Up	-4.7	5.7	15.2	50	2.1	6.8	2.1	6.8	259.1	850	0	1.09	0	3	2	-.25
167	Castor	C	-3	Up	-5.9	5.2	30.5	100	0	0	-1.6	-5.4	243.8	800	-1.5	1.01	3	4.5	8	-.13
168	Castor	C	-3	Up	-16.4	5.2	0	0	0	0	0	0	243.8	800	2	1.02	0	10	7.5	-.51
169	Castor	C	-3	Up	-15	9.8	0	0	0	0	.6	2	228.6	750	1	1.02	-.5	9.5	5	-.18
170	Castor	C	-3	Up	-13.3	5.2	0	0	1.1	3.5	1.1	3.5	228.6	750	.7	1.02	.3	9	10	-.4
171	Castor	C	-3	Up	-13.3	11	30.5	100	0	0	1.3	4.2	228.6	750	-1.5	1.08	0	12	11	-.31
172	Castor	C	-3	Up	-9.1	8.2	61.0	200	0	0	1.1	3.7	213.4	700	-1	1.08	1	8.3	6	-.19
173	Castor	C	-3	Up	-14.6	6.1	30.5	100	.9	3.1	.9	3.1	243.8	800	-3	1.13	.5	13.5	9.5	-.41
174	Castor	C	-3	Up	-12.6	6.8	30.5	100	.9	3.1	1.3	4.2	243.8	800	-1.6	1.08	-1.6	9.5	4.3	-.35
175	Castor	C	-3	Up	-27.2	6.4	-15.2	-50	4.4	14.4	-7.3	-24	381.0	1250	1.5	1.15	-3	18	30	-.42
176	Castor	C	-3	Up	-18.1	-.4	61.0	200	6.7	22.1	6.7	22.1	310.9	1020	-1	1.02	-3	15	18	-.38
177	Castor	C	-3	Up	-16.5	6.8	0	0	5.3	17.5	5.3	17.5	274.3	900	-1	1.02	-2	22	27	-.72
178	Castor	C	-3	Down	-22.4	2.3	91.4	300	3.7	12	-5.6	-18.4	280.4	920	-.5	1.01	-.3	.5	24	-.3
179	Castor	C	-3	Up	-27.3	.3	0	0	5.3	17.5	5.3	17.5	243.8	800	1	1.08	0	20.1	22.5	-.25
180	Castor	C	-3	Up	-18.5	3.3	-15.2	-50	4.4	14.4	4.4	14.4	259.1	850	-.5	1.12	-1.5	20.2	25.5	-.61
181	Castor	C	-3	Up	-20.2	.3	15.2	50	5.2	17	5.2	17	304.8	1000	-.5	1.07	-.5	15.5	24	-.28
182	Castor	C	-3	Up	-12.9	-1.4	-7.6	-25	4.3	14.2	4.3	14.2	281.9	925	-1	.97	-.8	18	26.5	-.58
183	Castor	C	-3	Up	-21.2	10.9	15.2	50	4.1	13.6	5.9	19.2	259.1	850	-1.5	.97	-1.5	21	20	-.54
184	Castor	C	-3	Up	-20.3	1.5	7.6	25	4.2	13.8	5.2	17.2	312.4	1025	-2	1.02	.3	18	18.5	-.37
185	Castor	C	-3	Up	-11.9	1.7	30.5	100	1.0	3.4	2.1	6.8	213.4	700	1	1.13	0	10.5	7.5	-.24
186	Castor	C	-3	Up	-12.6	6.2	0	0	1.1	3.5	1.1	3.5	233.8	767	1	1.00	1.5	8	23	-.27
187	Castor	C	-3	Up	-13.5	2.4	15.2	50	0	0	1.8	5.9	228.6	750	.3	1.04	.5	17.5	22.5	-.21
188	Castor	C	-3	Up	-12.2	8.7	15.2	50	.5	1.7	2.4	8.0	228.6	750	2.5	1.06	-.3	15	24	-.3
189	Castor	C	-3	Up	-12.8	6.8	-15.2	-50	2.2	7.1	2.2	7.1	228.6	750	0	.99	0	15	21.5	-.58
190	Castor	C	-3	Up	-16.5	3.4	0	0	1.1	3.5	1.1	3.5	243.8	800	----	----	----	-----	-----	-----
191	Castor	C	-3	Up	-16.2	3.9	22.9	75	0	0	.9	2.9	251.5	825	----	----	----	-----	-----	-----
192	Preset	C	-3	Up	14	.2	30.5	100	-1.0	-3.3	-10.7	-35	335.3	1100	1.8	1.08	.3	-5.4	-.5	-.45
193	Preset	C	-3	Up	12.6	-4.6	15.2	50	-1.0	-3.4	-8.5	-28.0	350.5	1150	2.7	1.03	.5	-8.5	-7	-.4
194	Preset	C	-3	Up	8.7	-.3	-3.0	-10	-1.1	-3.5	-3.4	-11.2	368.8	1210	2.2	.99	2.3	-9.5	-5.5	-.18
195	Preset	C	-3	Up	8.0	-4.5	7.6	25	-2.1	-6.9	-4.7	-15.6	327.7	1075	1.0	1.01	1.5	-8.8	-4.5	-.2

[a]Crosswind is positive for crosswind from right.
[b]Wind component parallel to runway is positive for headwind.
[c]Longitudinal touchdown dispersion is positive for landing long of touchdown point.
[d]Lateral touchdown dispersion is positive for landing to pilot's right of runway center line.
[e]Maximum lateral dispersion is positive for landing to pilot's right of runway center line.

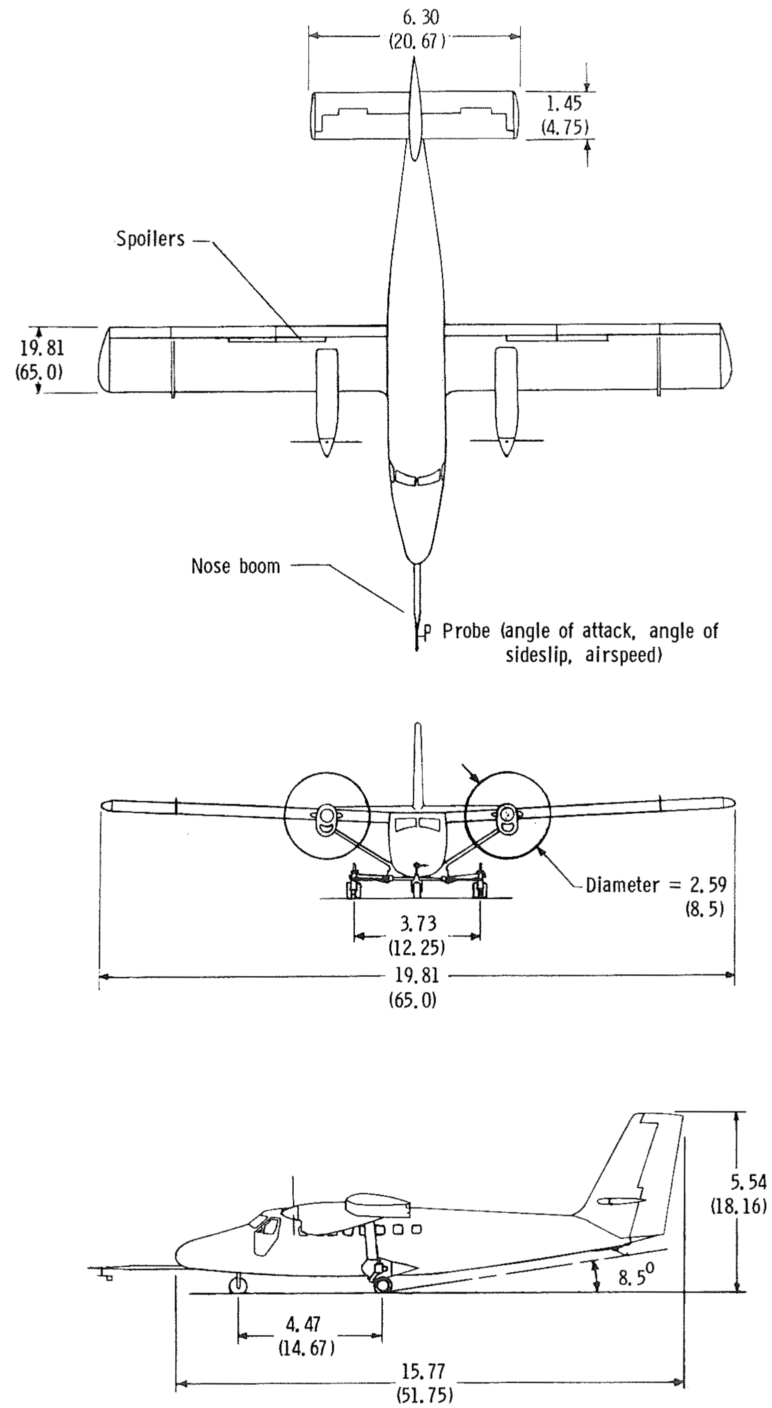


Figure 1.- Three-view drawing of test airplane with modifications for crosswind-landing-gear program. All dimensions are in meters (feet).

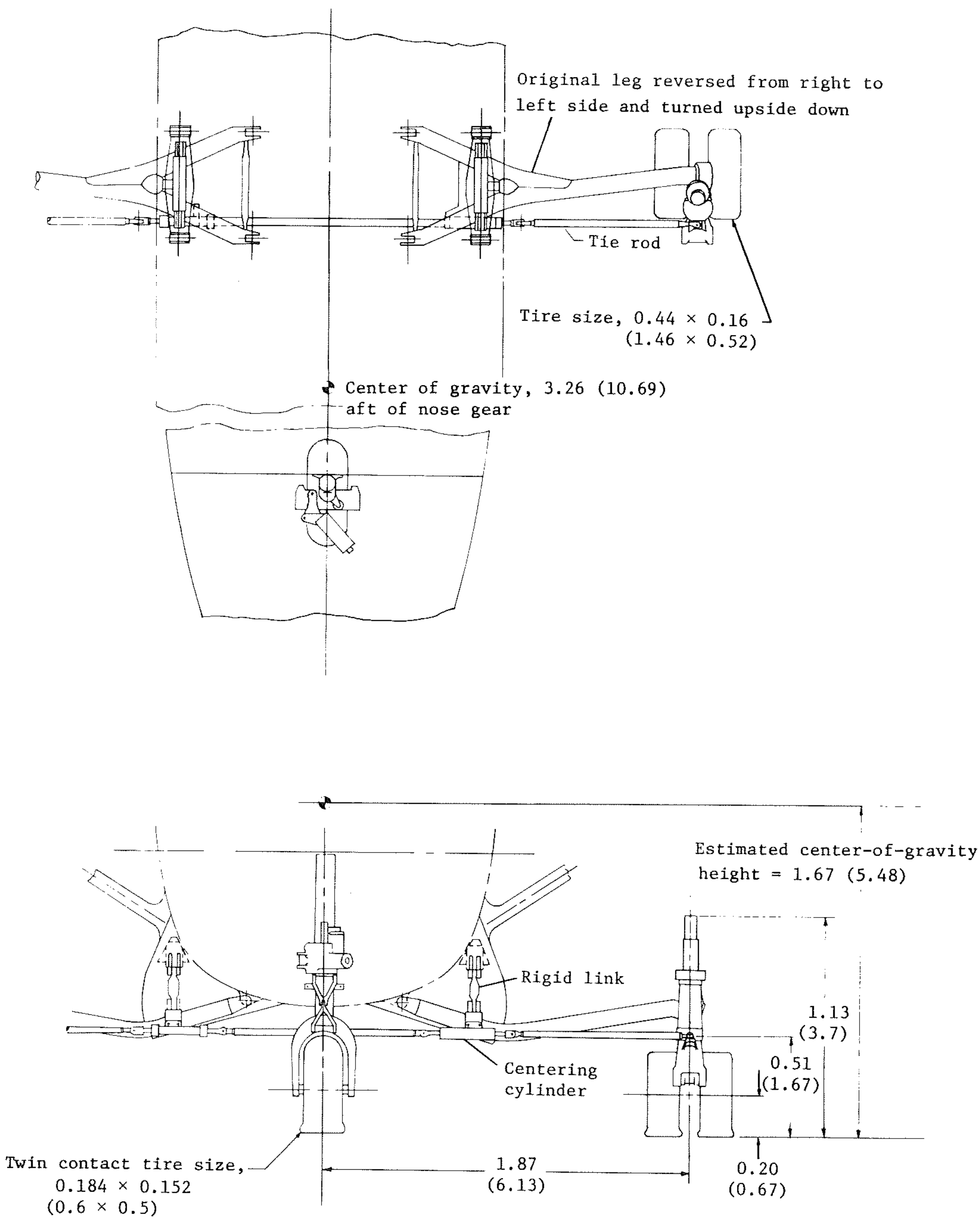
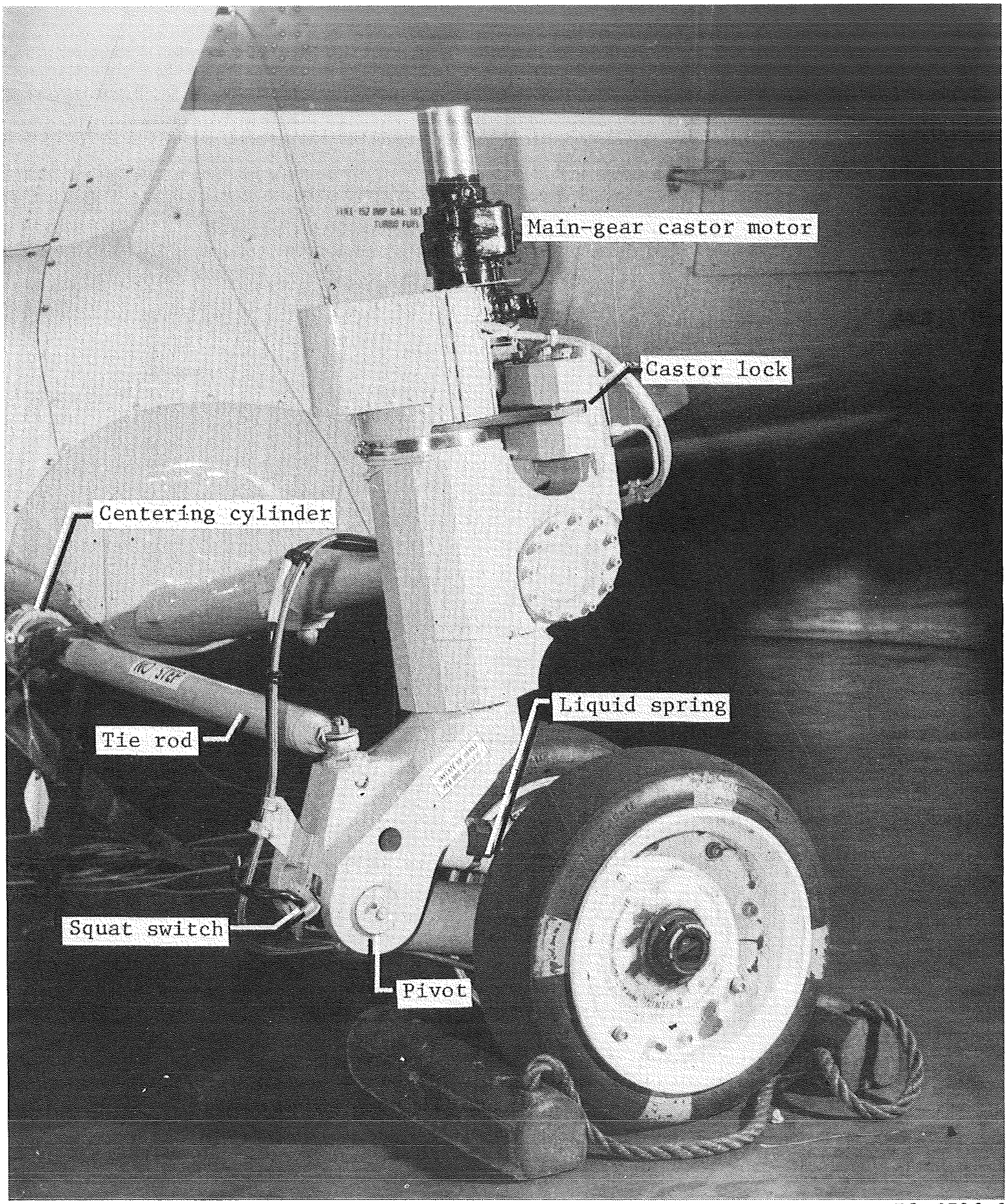


Figure 2.- Detailed views of crosswind landing gear. All dimensions are in meters (feet).



L-76-6586.1

Figure 3.- Left main-gear unit.

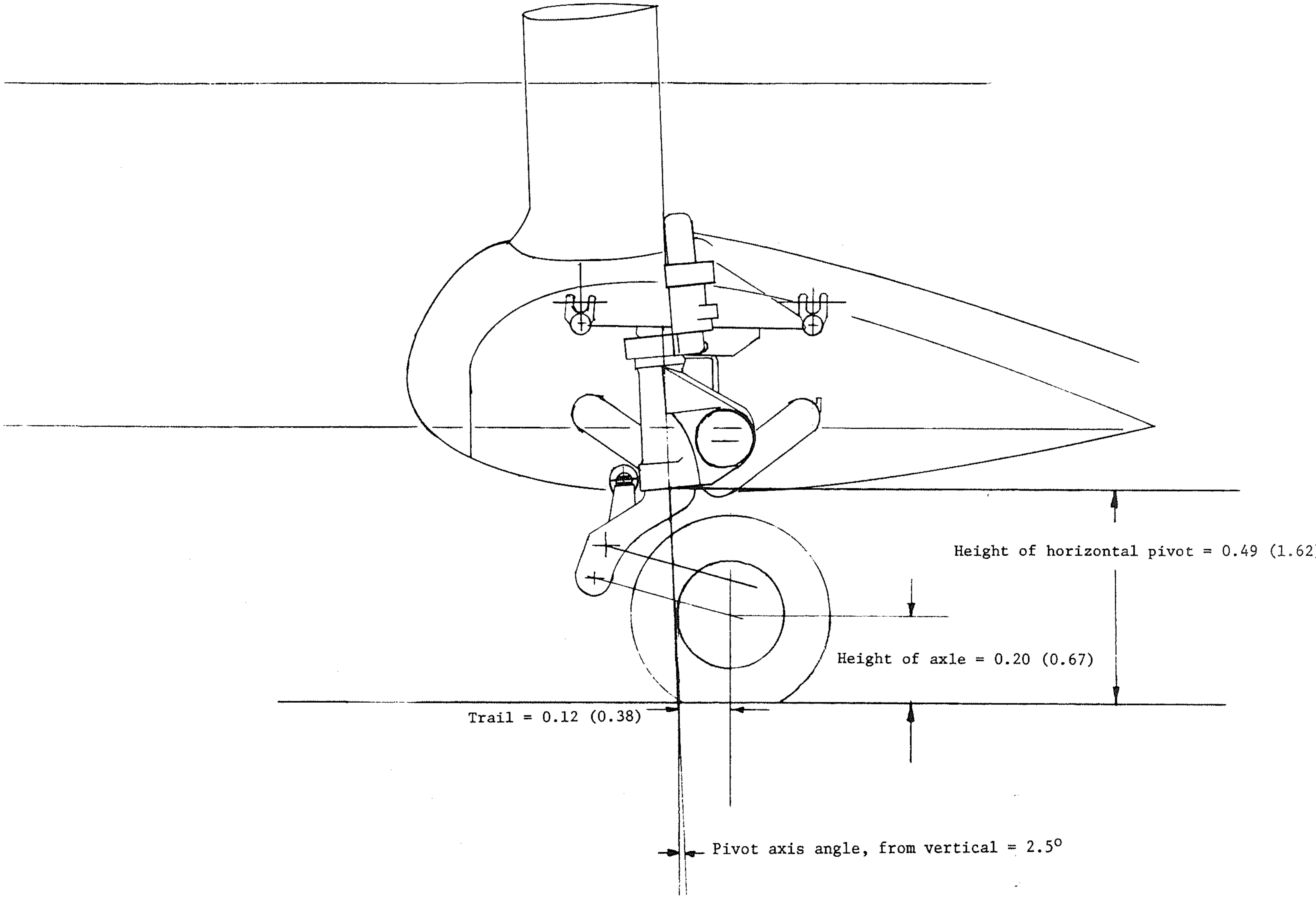
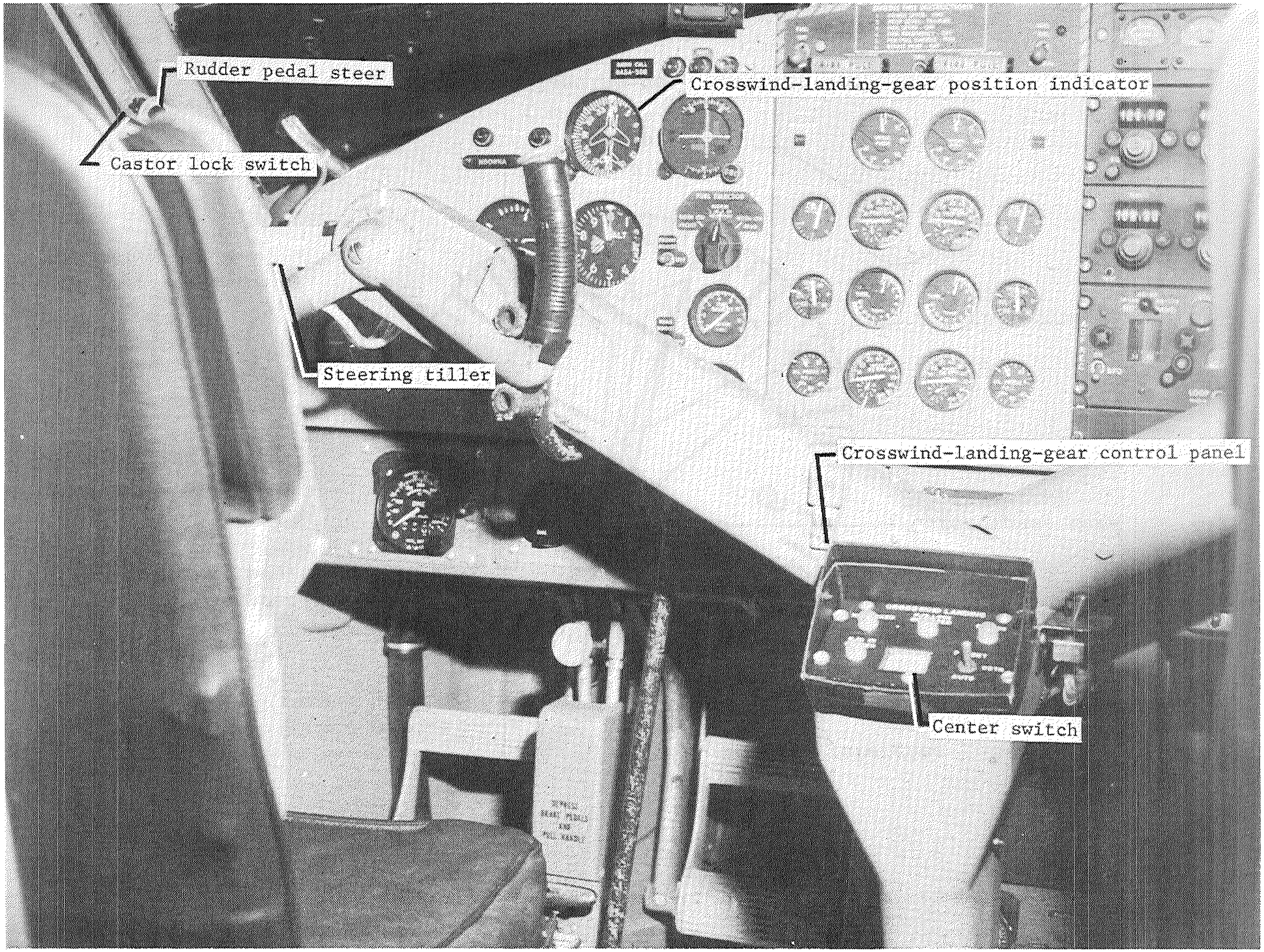


Figure 3.- Concluded.



L-76-6593.1

Figure 4.- Instrument panel for crosswind-landing-gear test airplane.

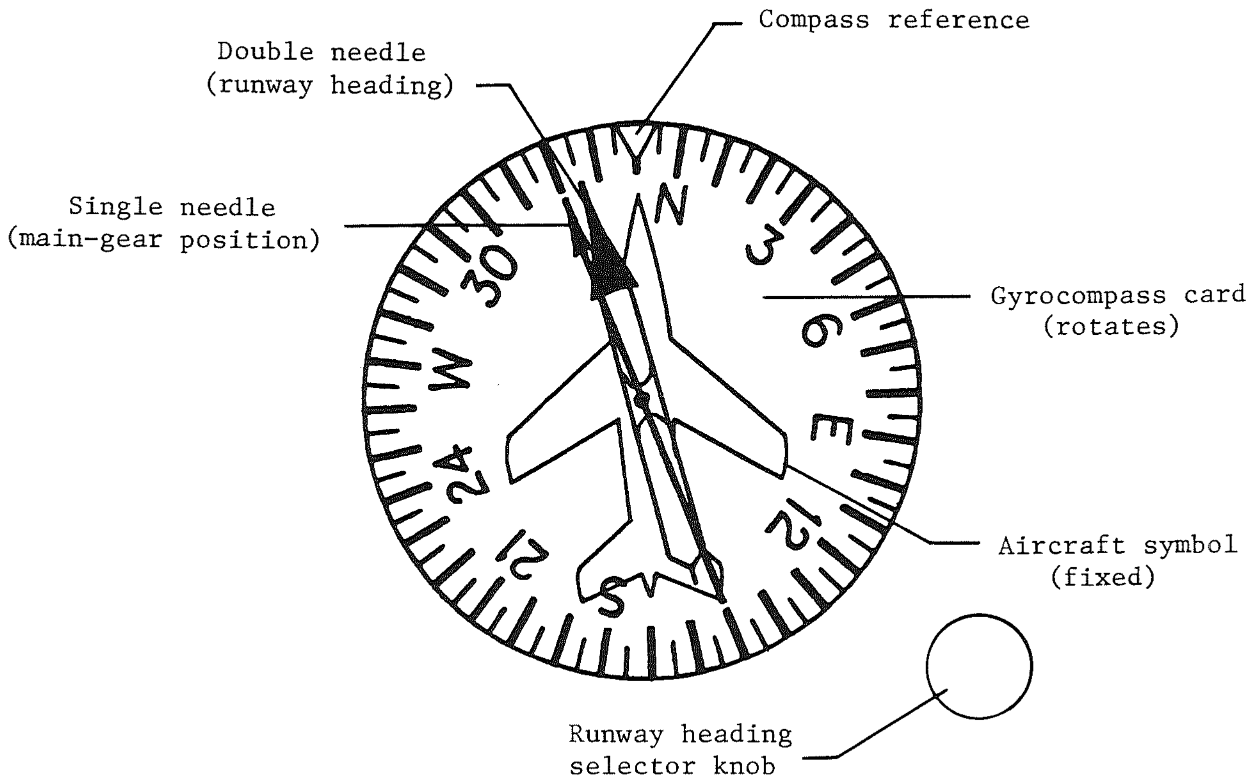


Figure 5.- Crosswind-landing-gear position indicator.

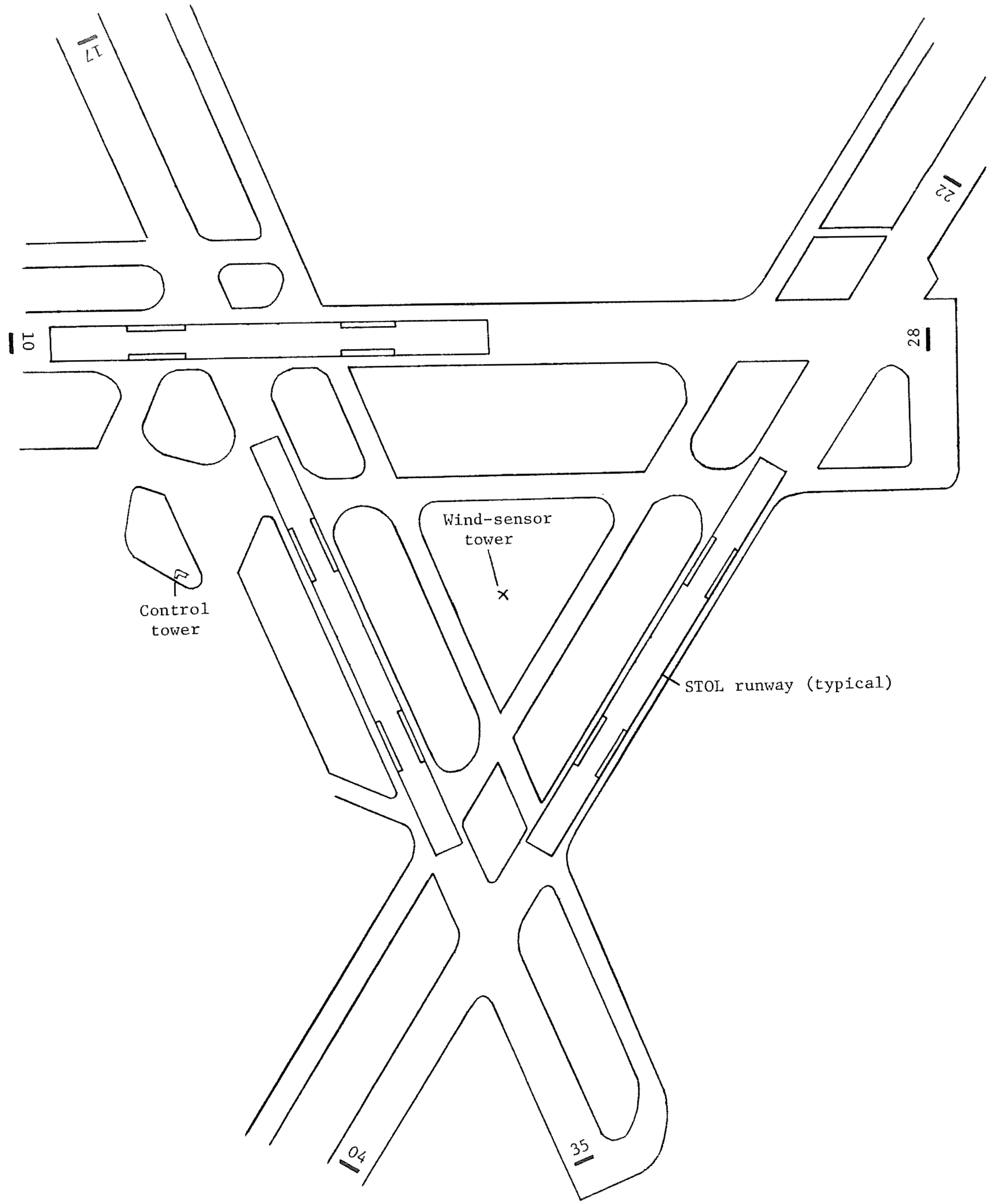


Figure 6.- Test site.

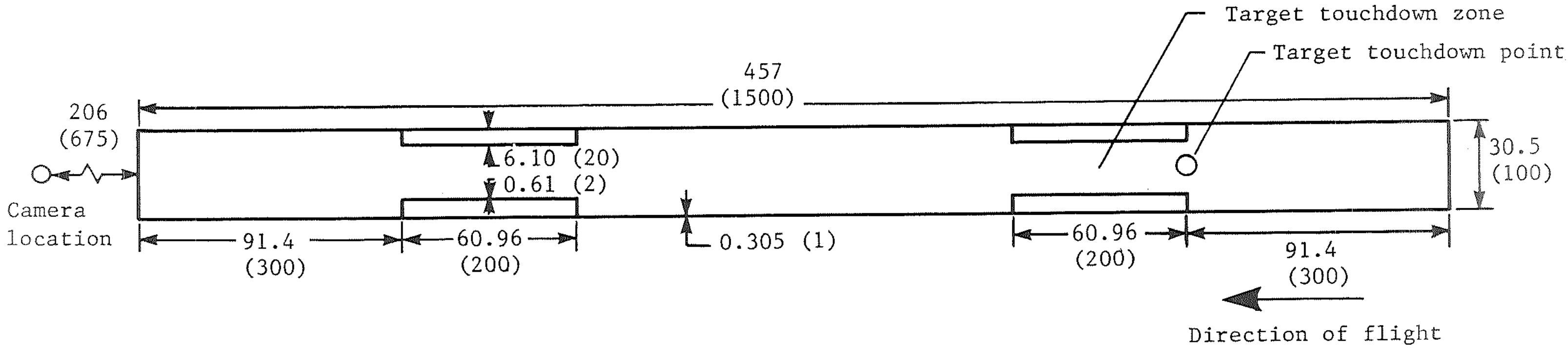
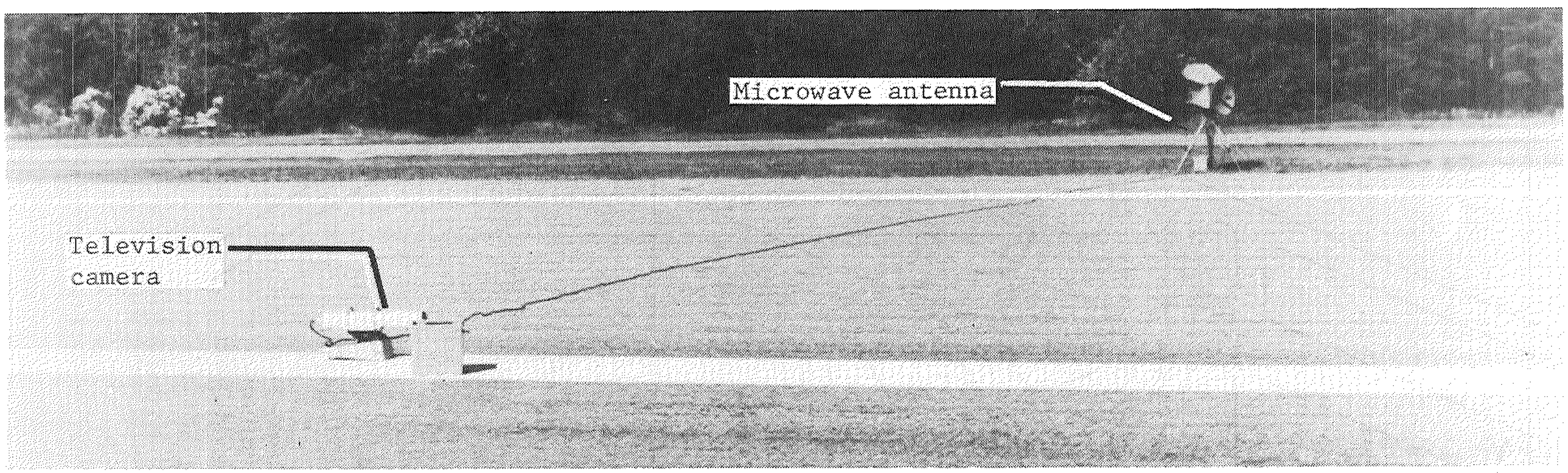
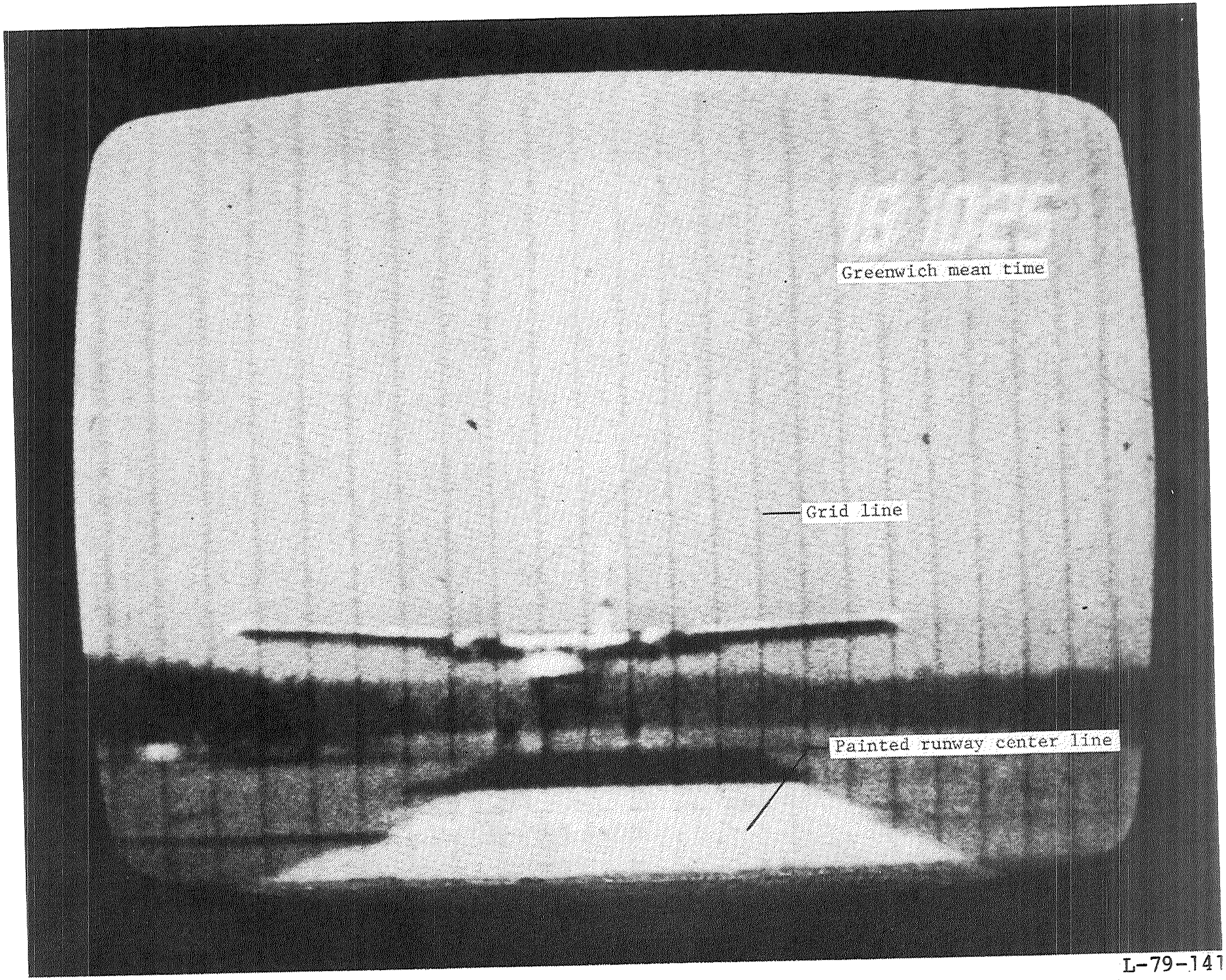


Figure 7.- Typical STOL runway marking for test airfield. All dimensions are in meters (feet).



L-79-140

Figure 8.- Television camera and microwave antenna for runway center-line picture.



L-79-141

Figure 9.- Typical television picture from camera on runway center line.

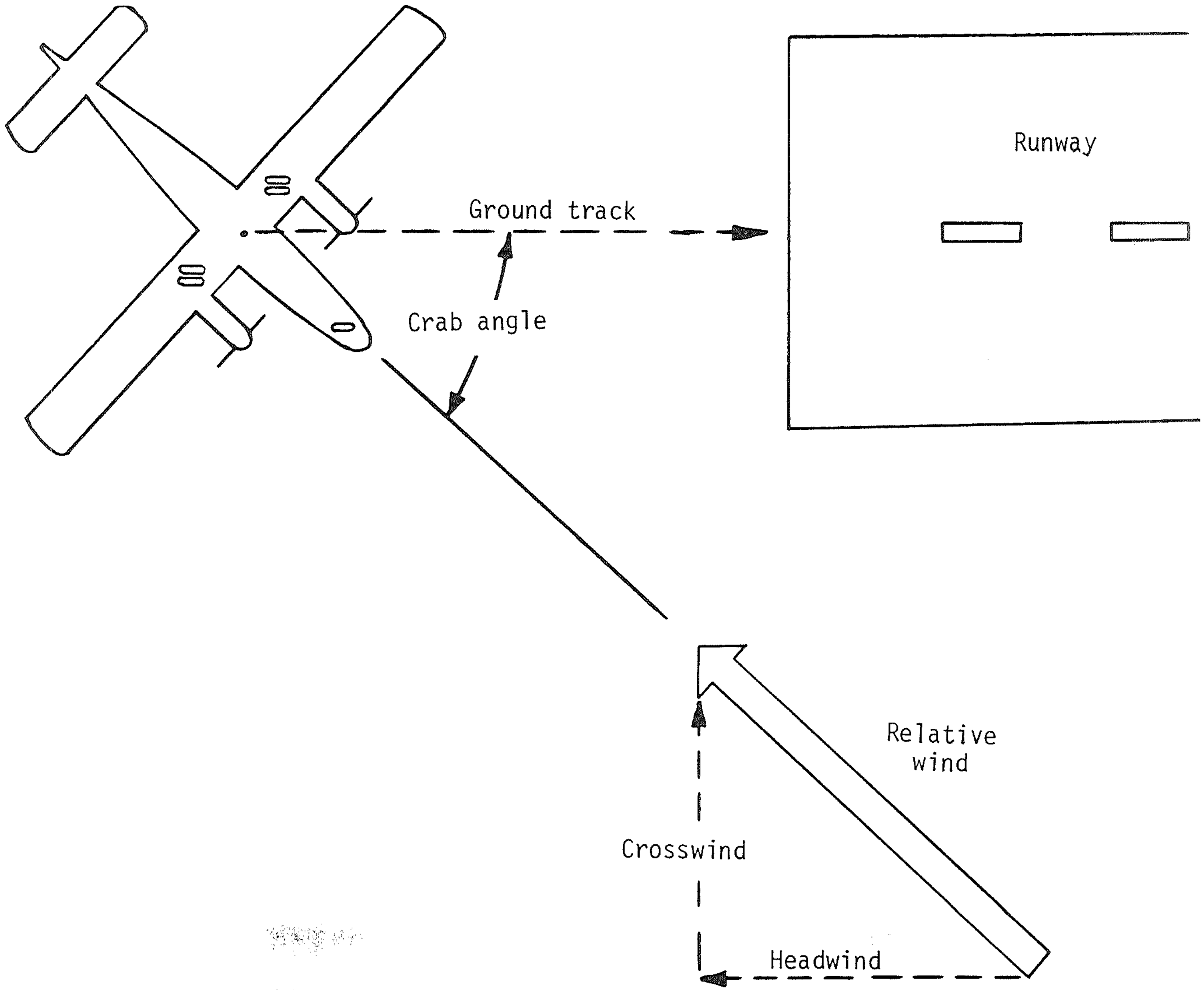


Figure 10.- Schematic of typical crosswind landing with crosswind gear.

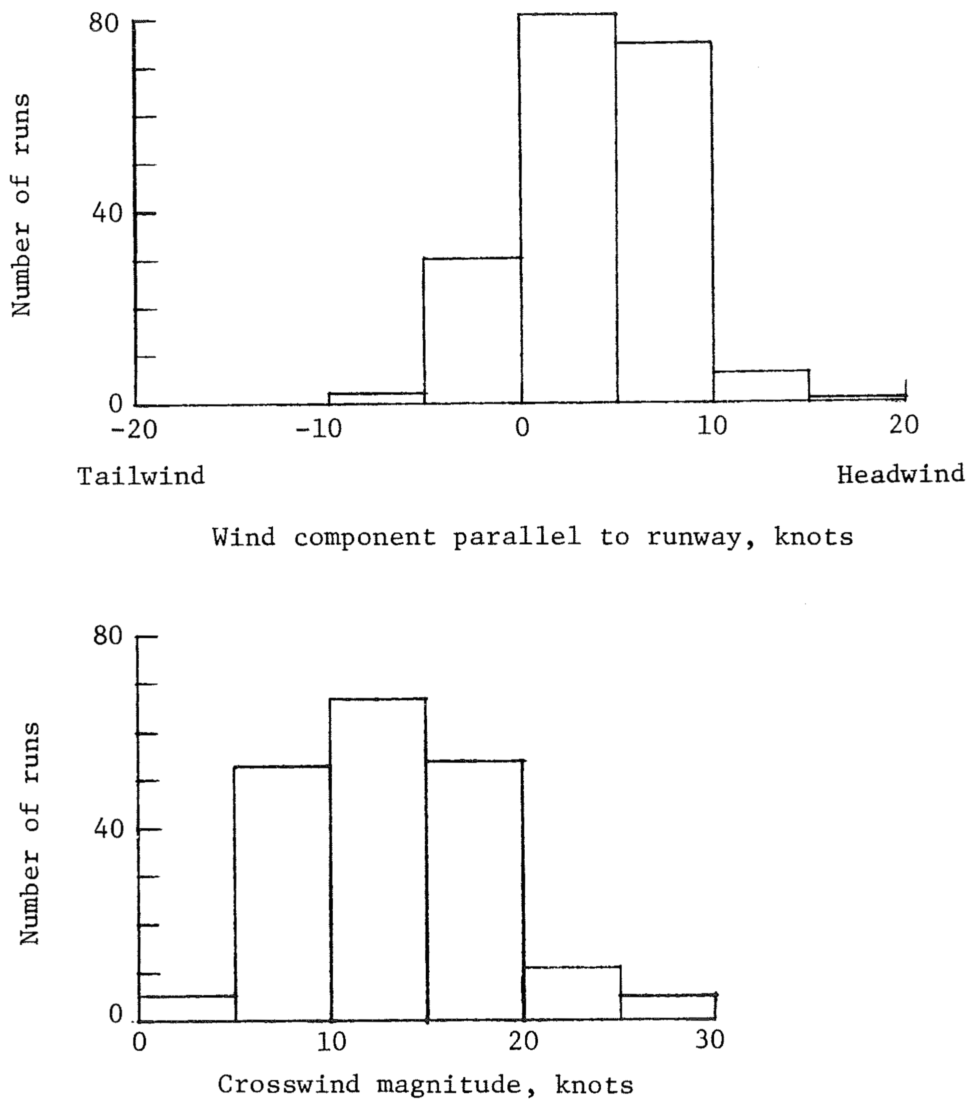
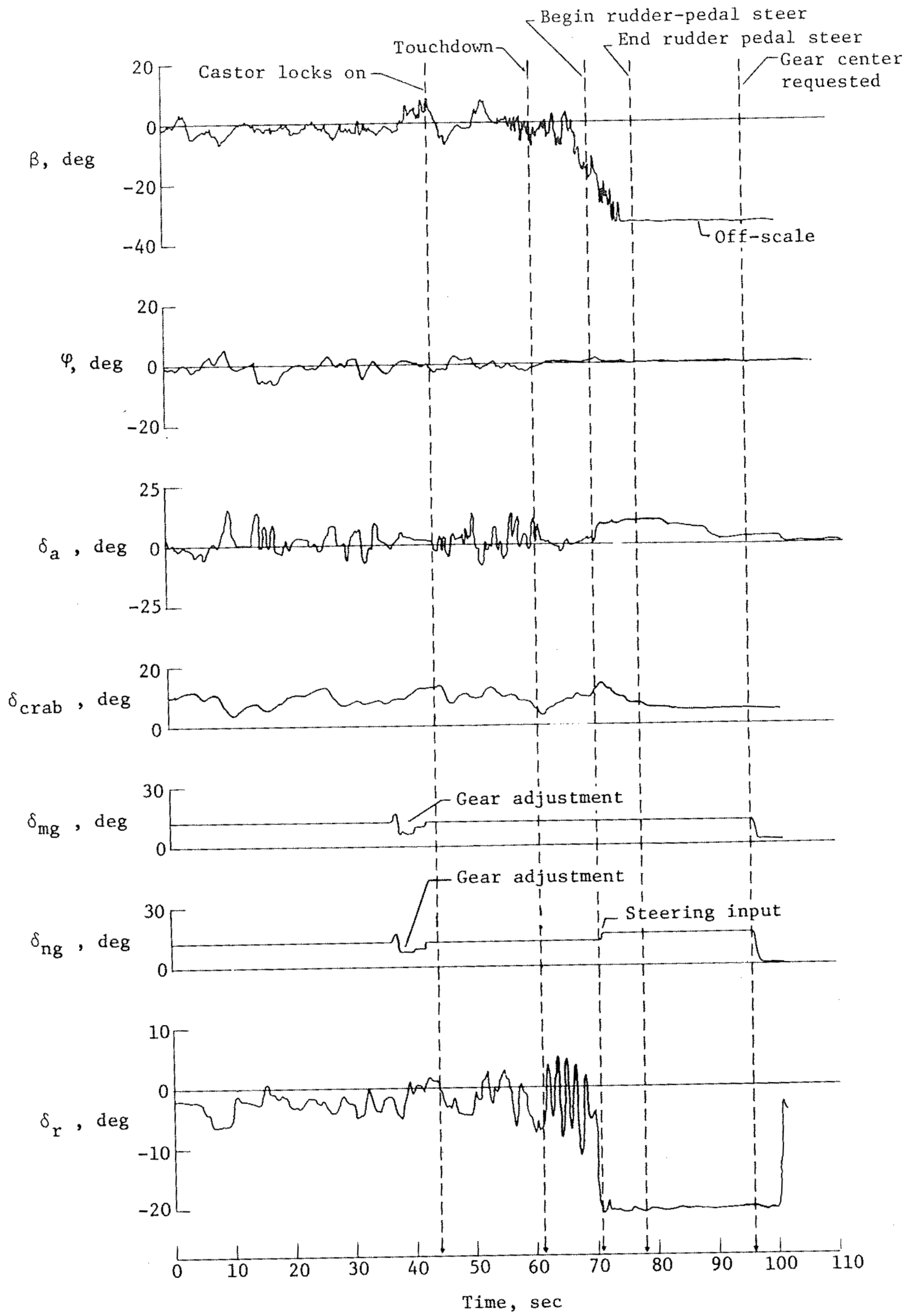
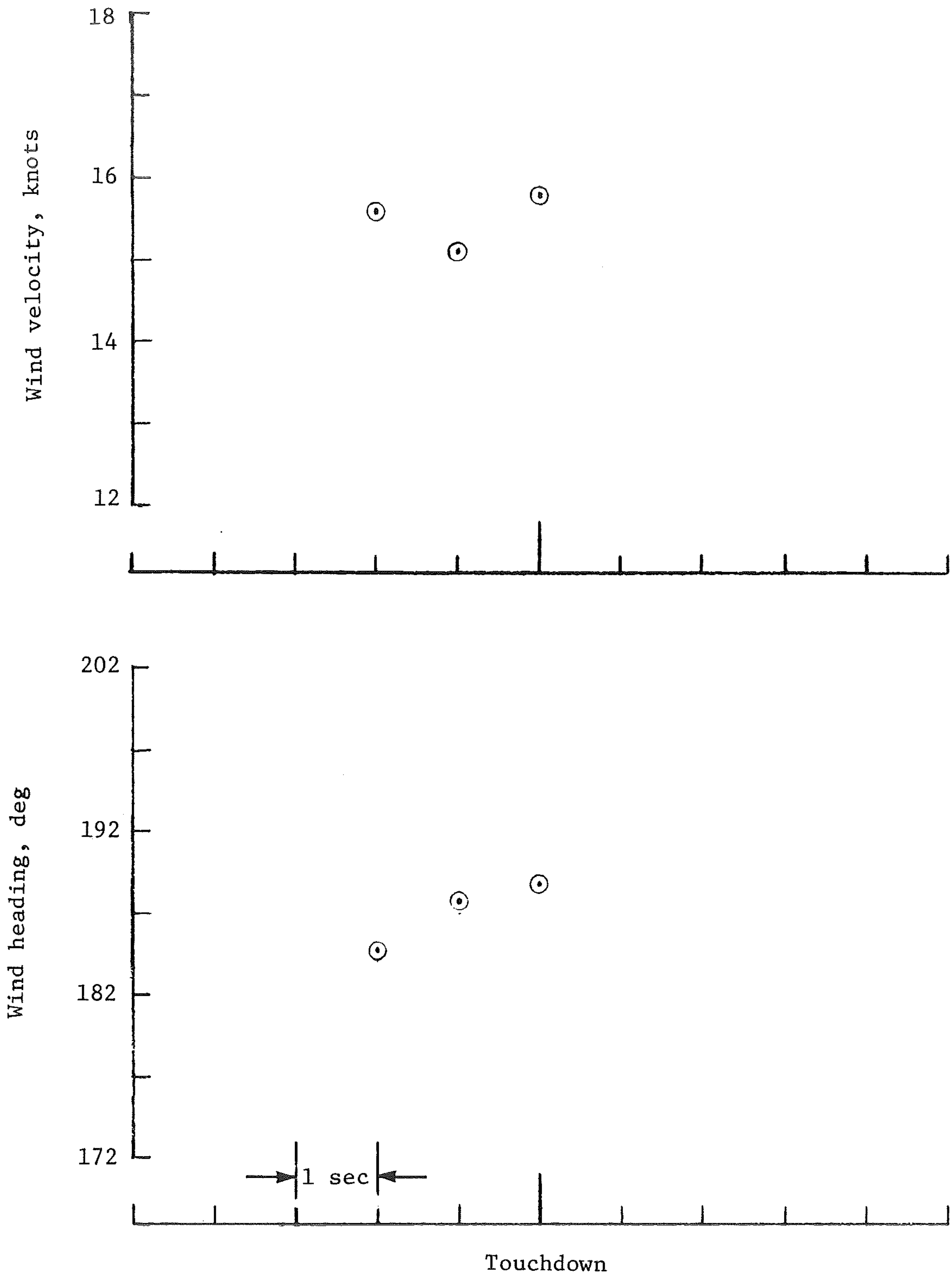


Figure 11.- Summary of wind conditions for all tests. Data based on readings from wind sensor at 6.1 m (20 ft) on wind-sensor tower.



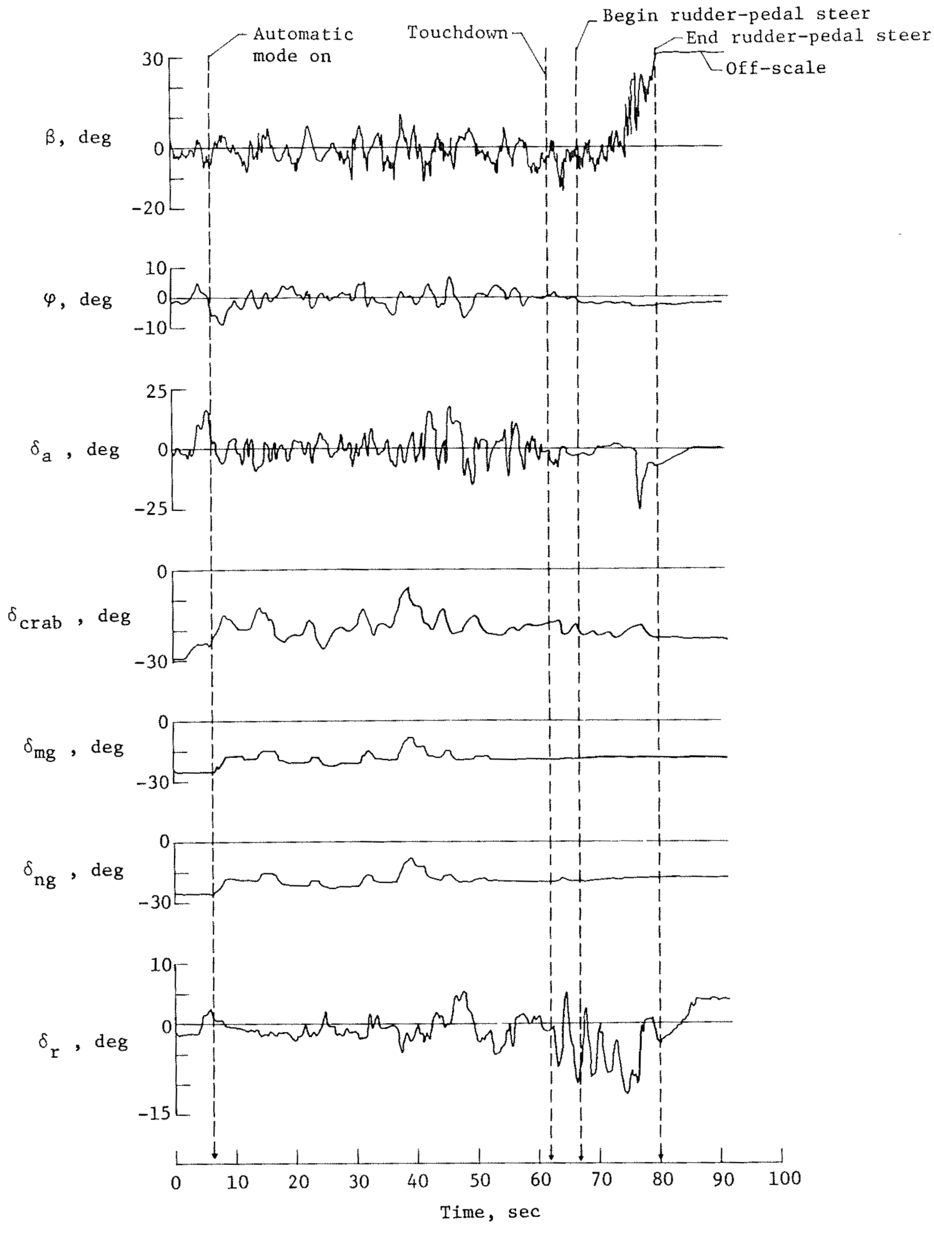
(a) Preset-mode landing with left crosswind of 15.6 knots.

Figure 12.- Crosswind landing time histories.



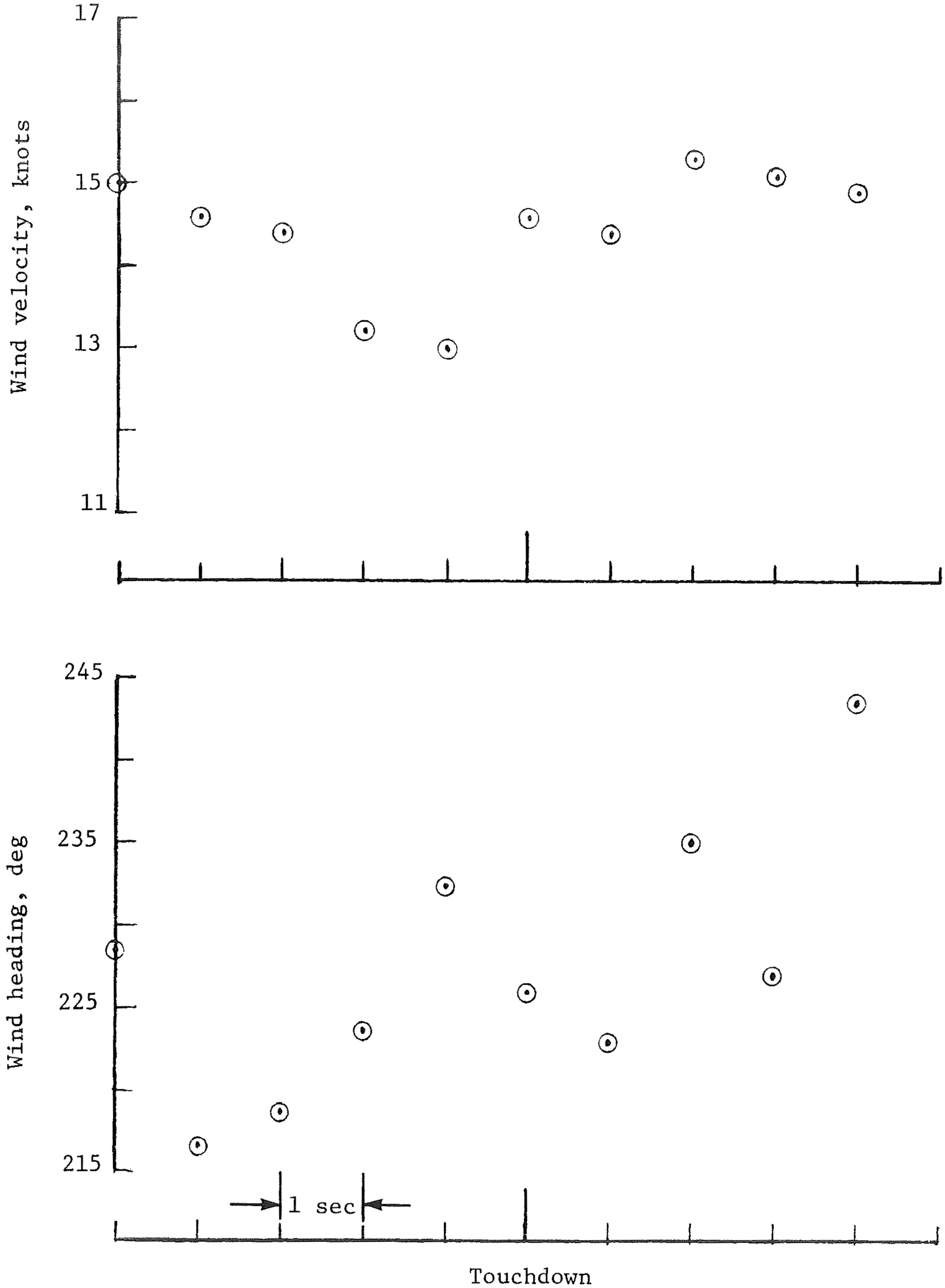
(a) Concluded.

Figure 12.- Continued.



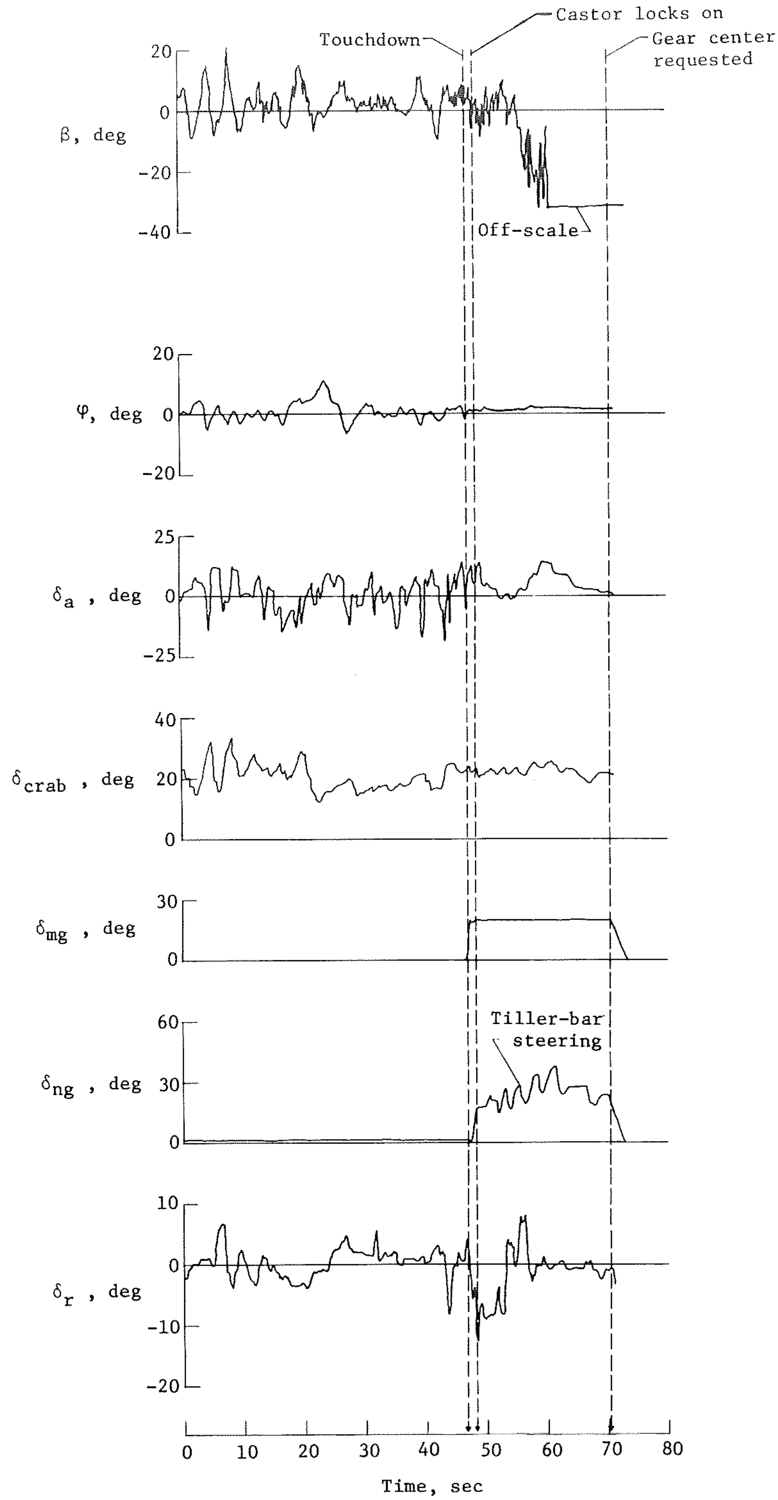
(b) Automatic-mode landing with right crosswind of 13.6 knots.

Figure 12.- Continued.



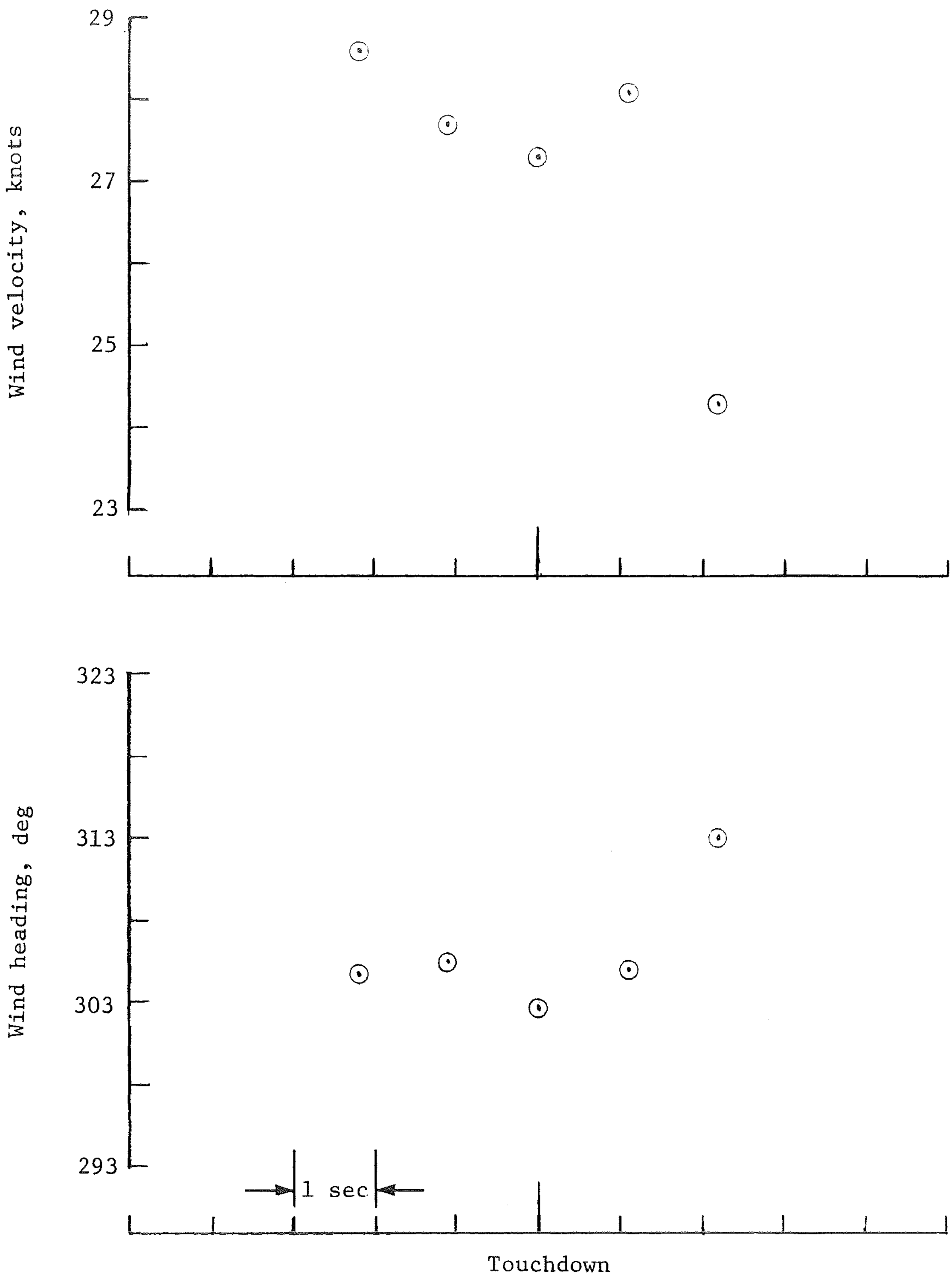
(b) Concluded.

Figure 12.- Continued.



(c) Castor-mode landing with left crosswind of 27.3 knots.

Figure 12.- Continued.



(c) Concluded.

Figure 12.- Concluded.

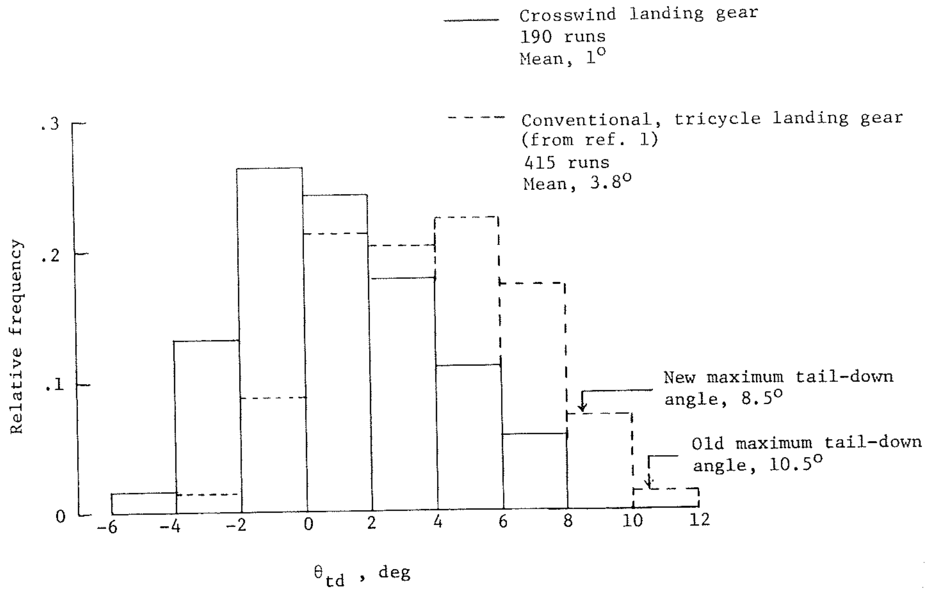


Figure 13.- Pitch attitude at touchdown. Data combined for all pilots, crosswinds, modes of crosswind-landing-gear operation, and both approach angles.

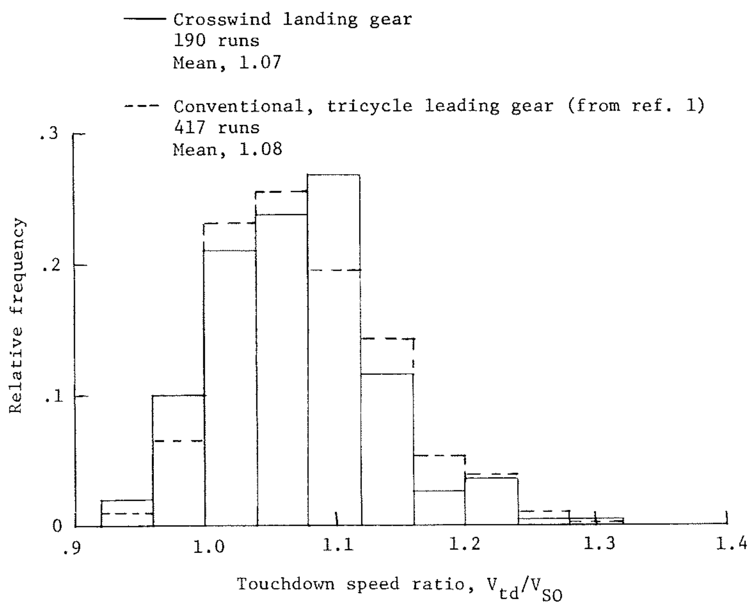


Figure 14.- Touchdown speed ratios. Data combined for all crosswinds, pilots, modes of crosswind-landing-gear operation and both approach angles.

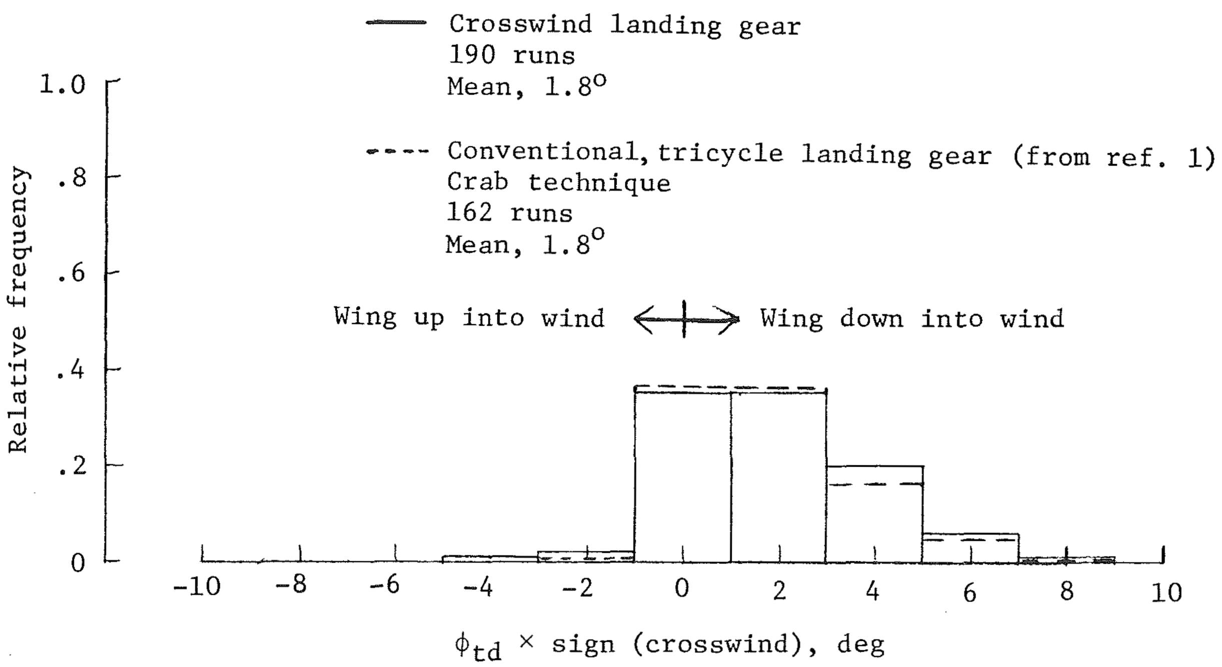


Figure 15.- Roll attitude at touchdown. Data combined for all crosswinds, pilots, modes of crosswind-landing-gear operation, and both approach angles.

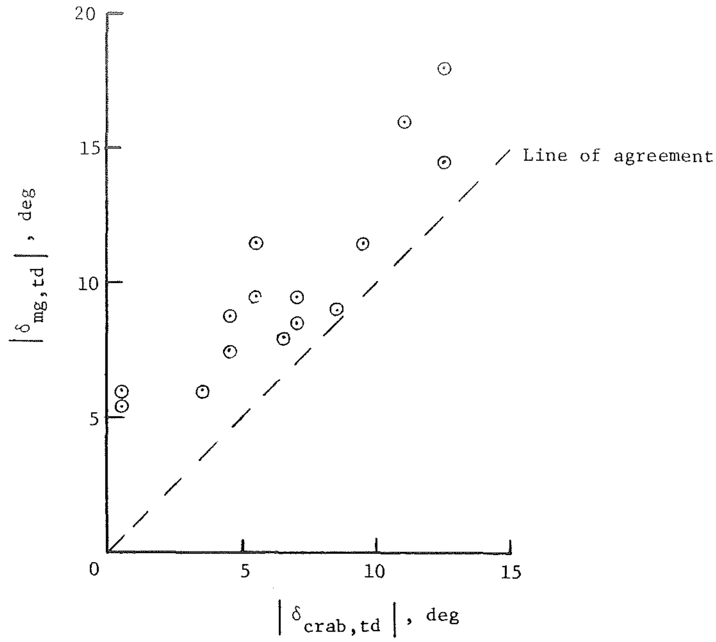


Figure 16.- Comparison of main-gear angle and crab angle at touchdown for preset-mode landings. Data combined for all crosswinds, pilots, and both approach angles.

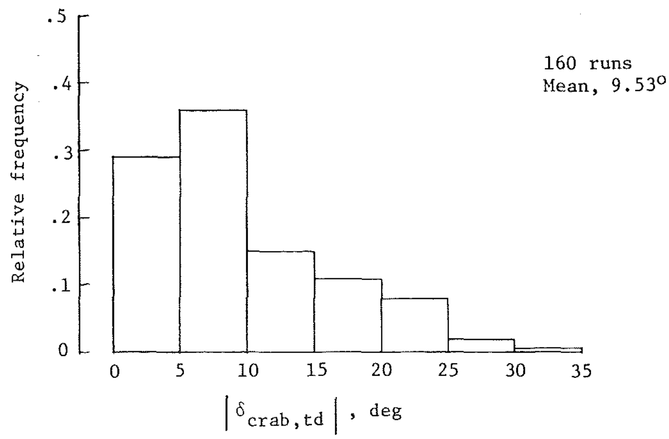


Figure 17.- Crab angle magnitude at touchdown. Data combined for all crosswinds, pilots, modes of crosswind-landing-gear operation, and both approach angles.

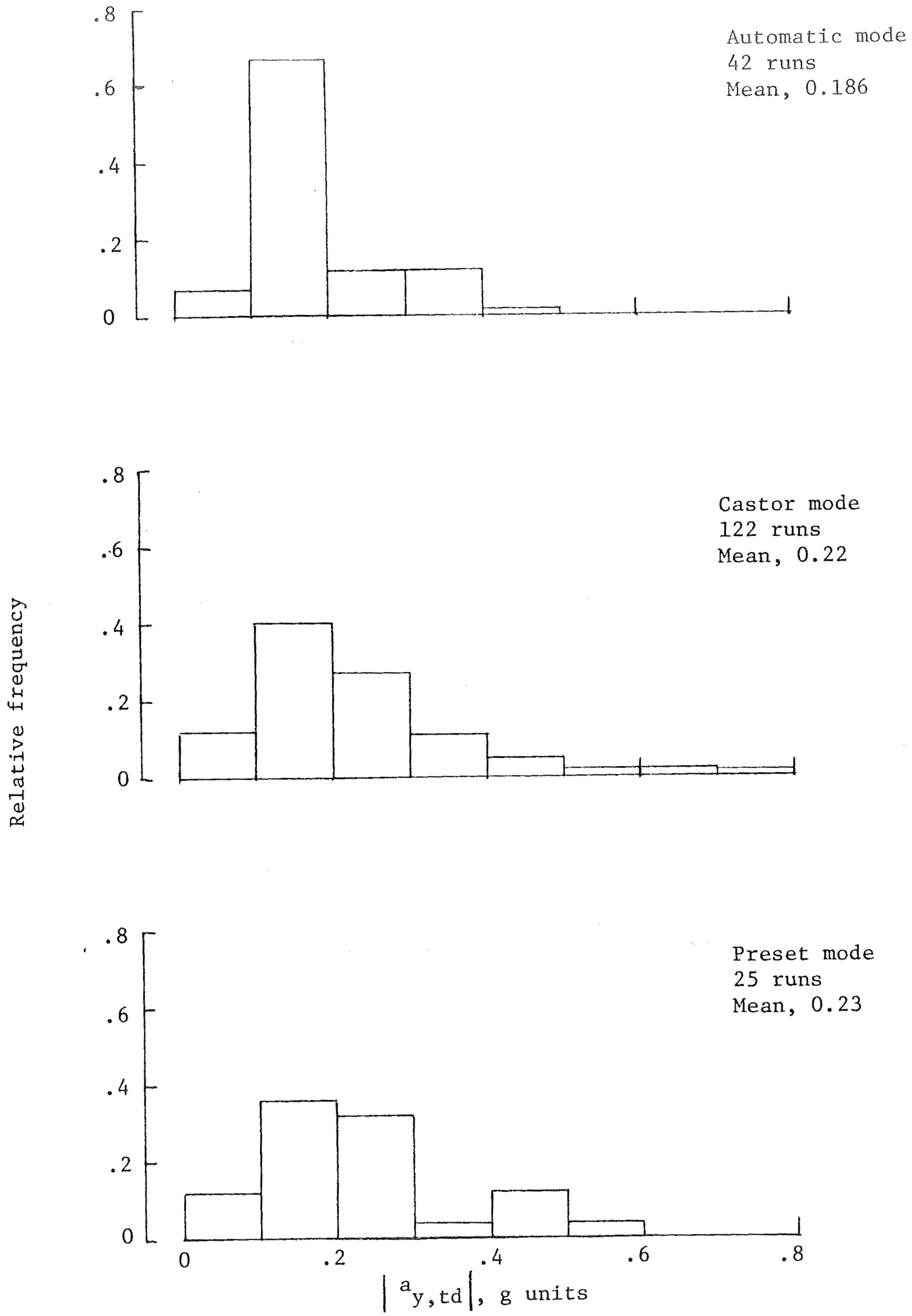


Figure 18.- Lateral acceleration magnitude at touchdown as a function of crosswind-landing-gear modes of operation. Data combined for all crosswinds, pilots, and both approach angles.

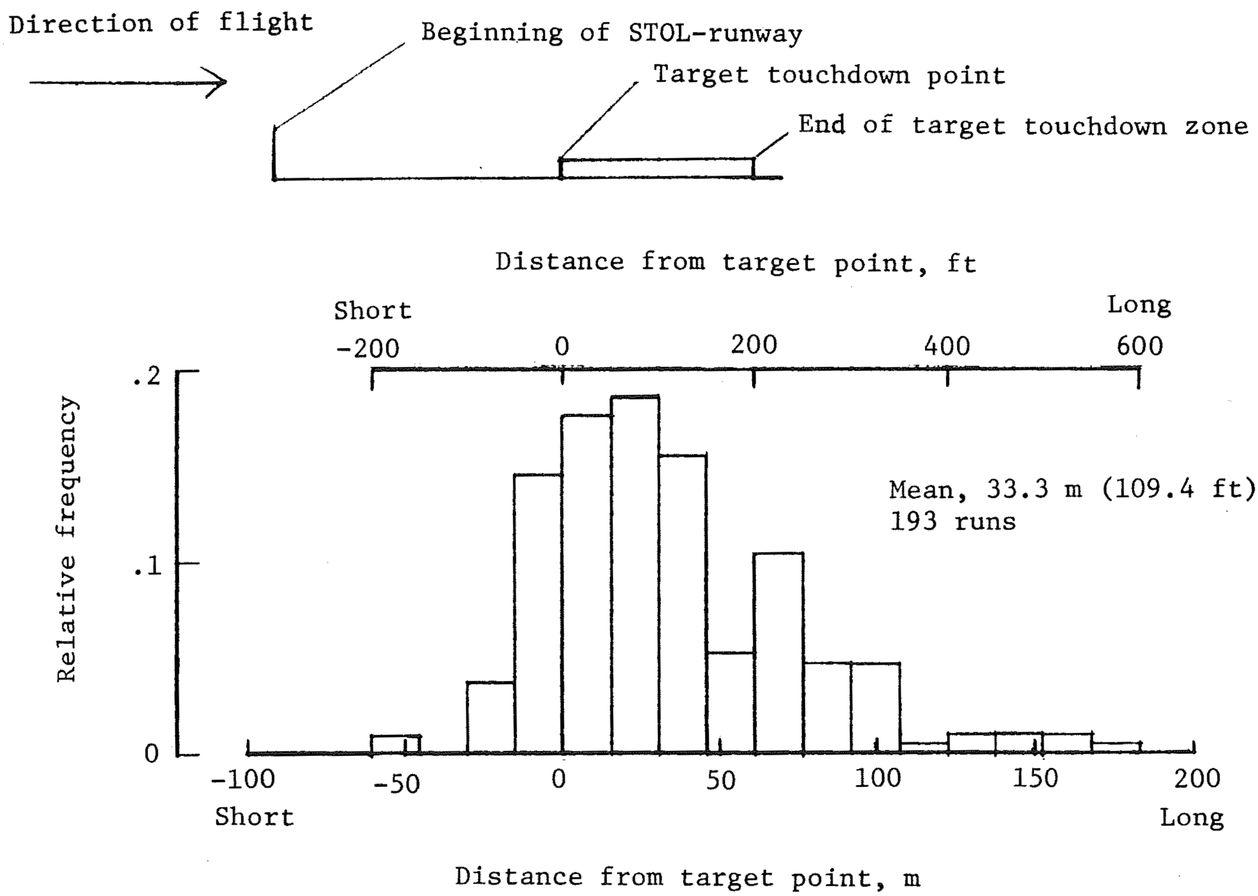


Figure 19.- Longitudinal touchdown dispersion. Data combined for all crosswinds, pilots, modes of crosswind-landing-gear operation, and both approach angles.

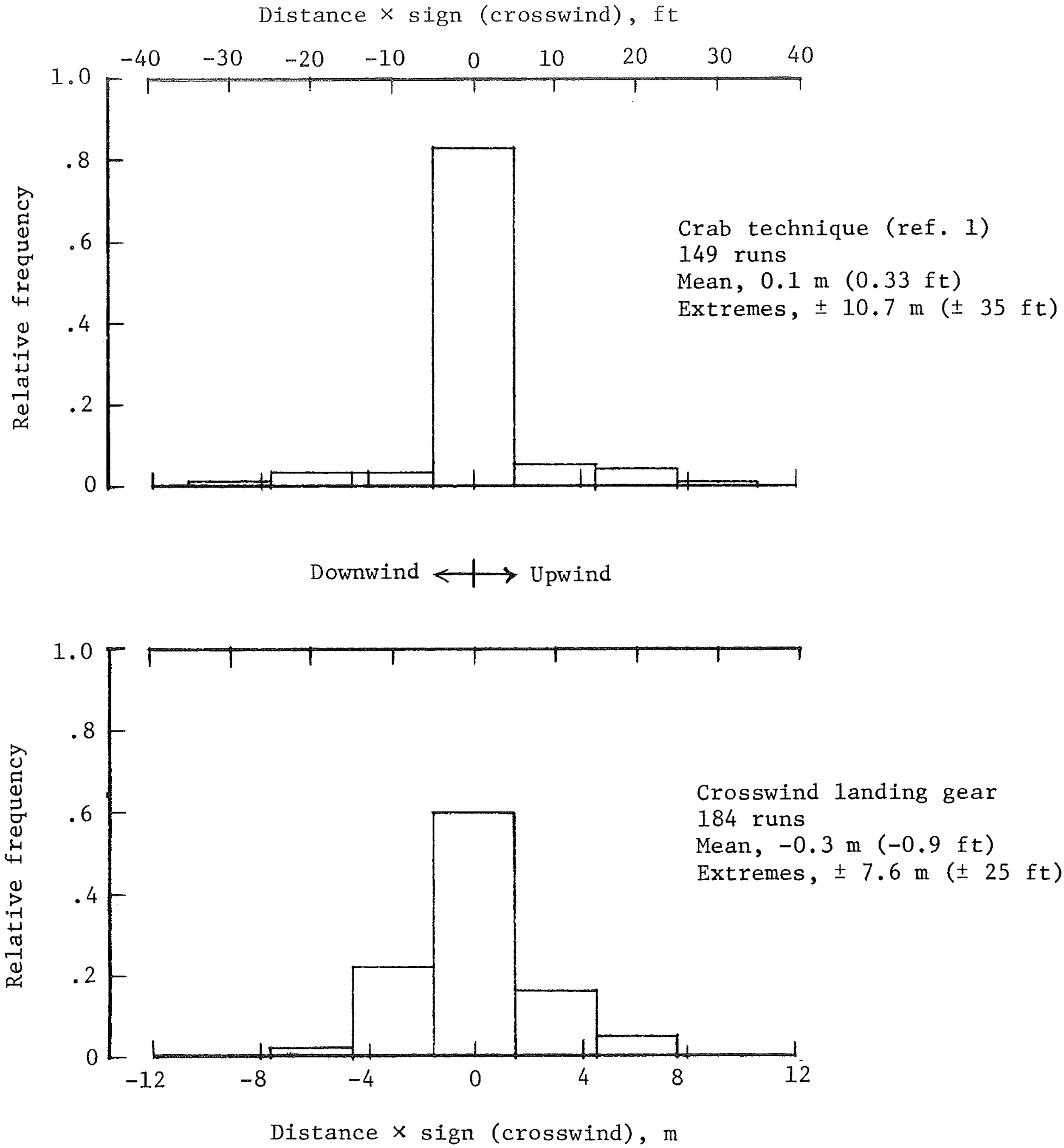


Figure 20.- Lateral touchdown dispersion. Data combined for all crosswinds, pilots, crosswind-landing-gear modes of operation, and both approach angles. Crab-technique data are from reference 1.

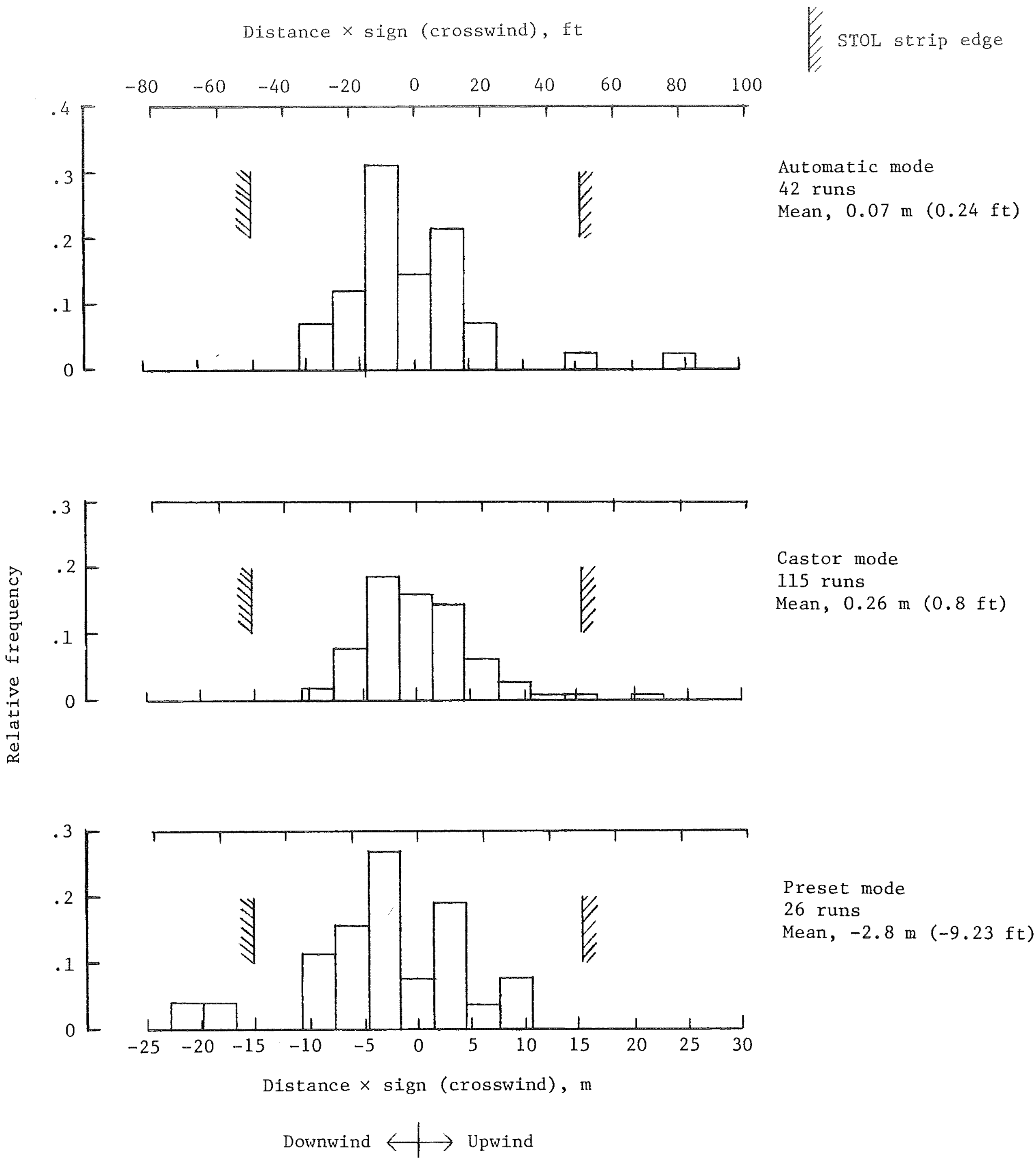


Figure 21.- Maximum lateral dispersion from runway center line during ground roll-out. Data combined for all crosswinds, pilots, and both approach angles.

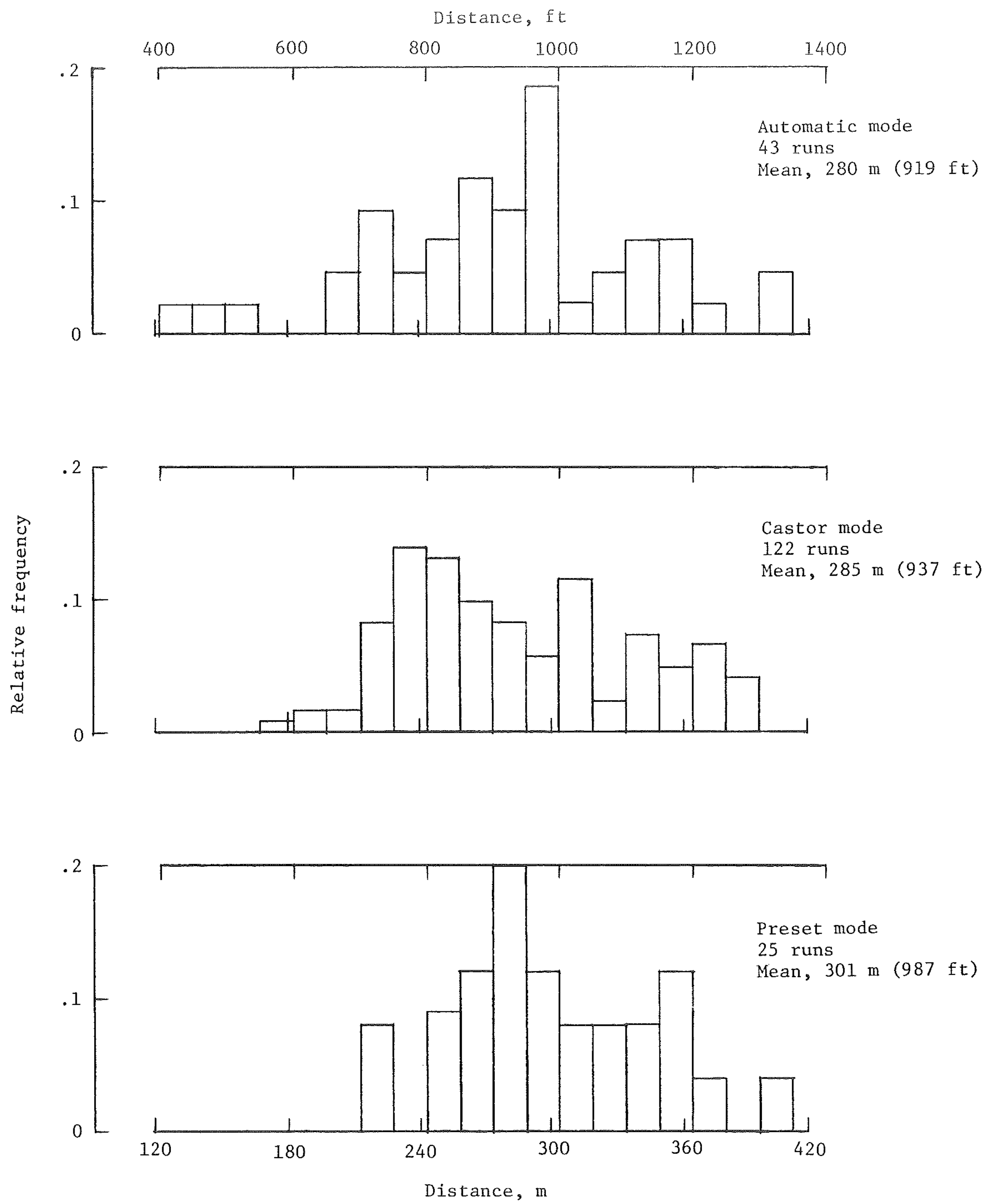
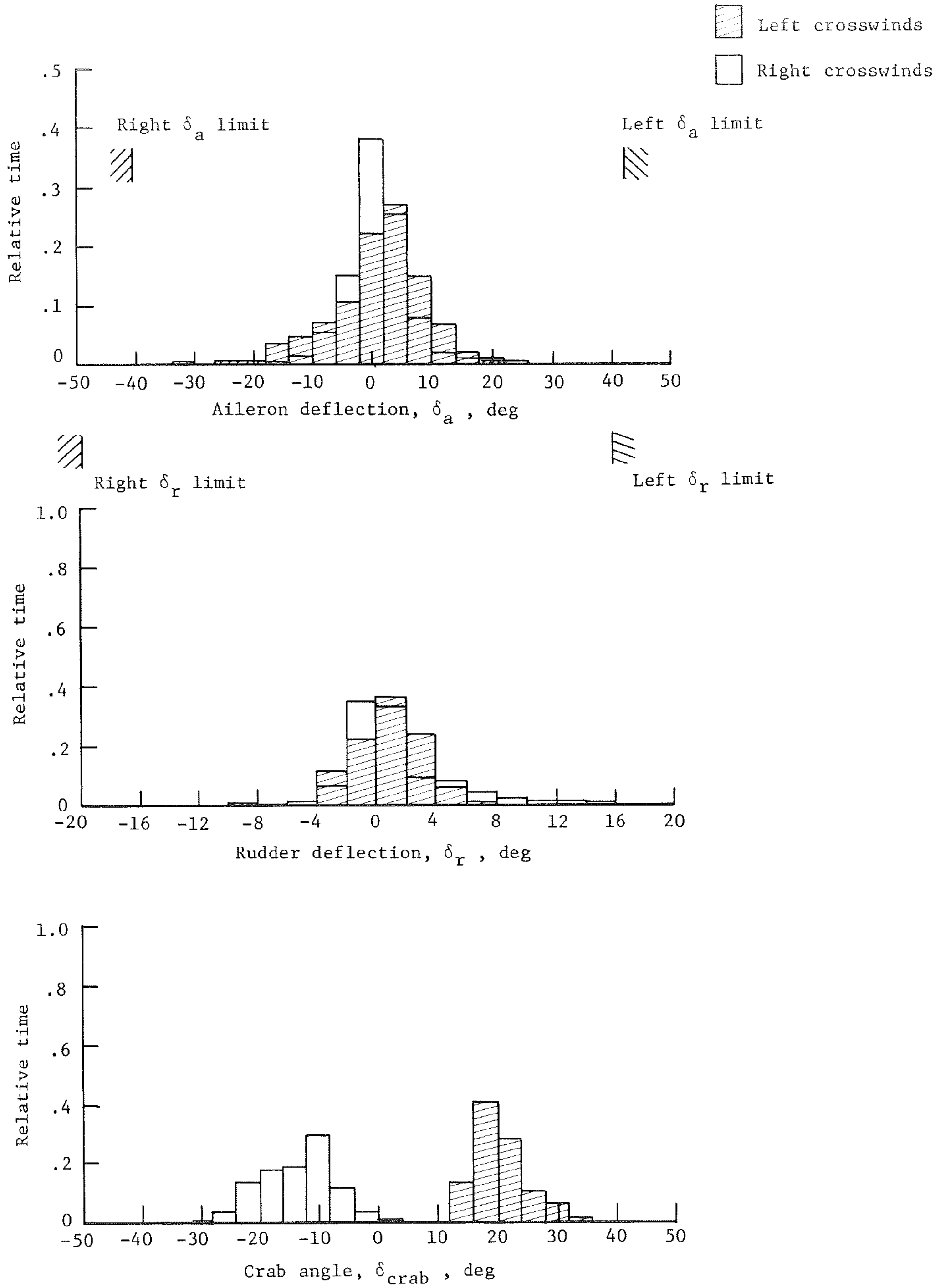
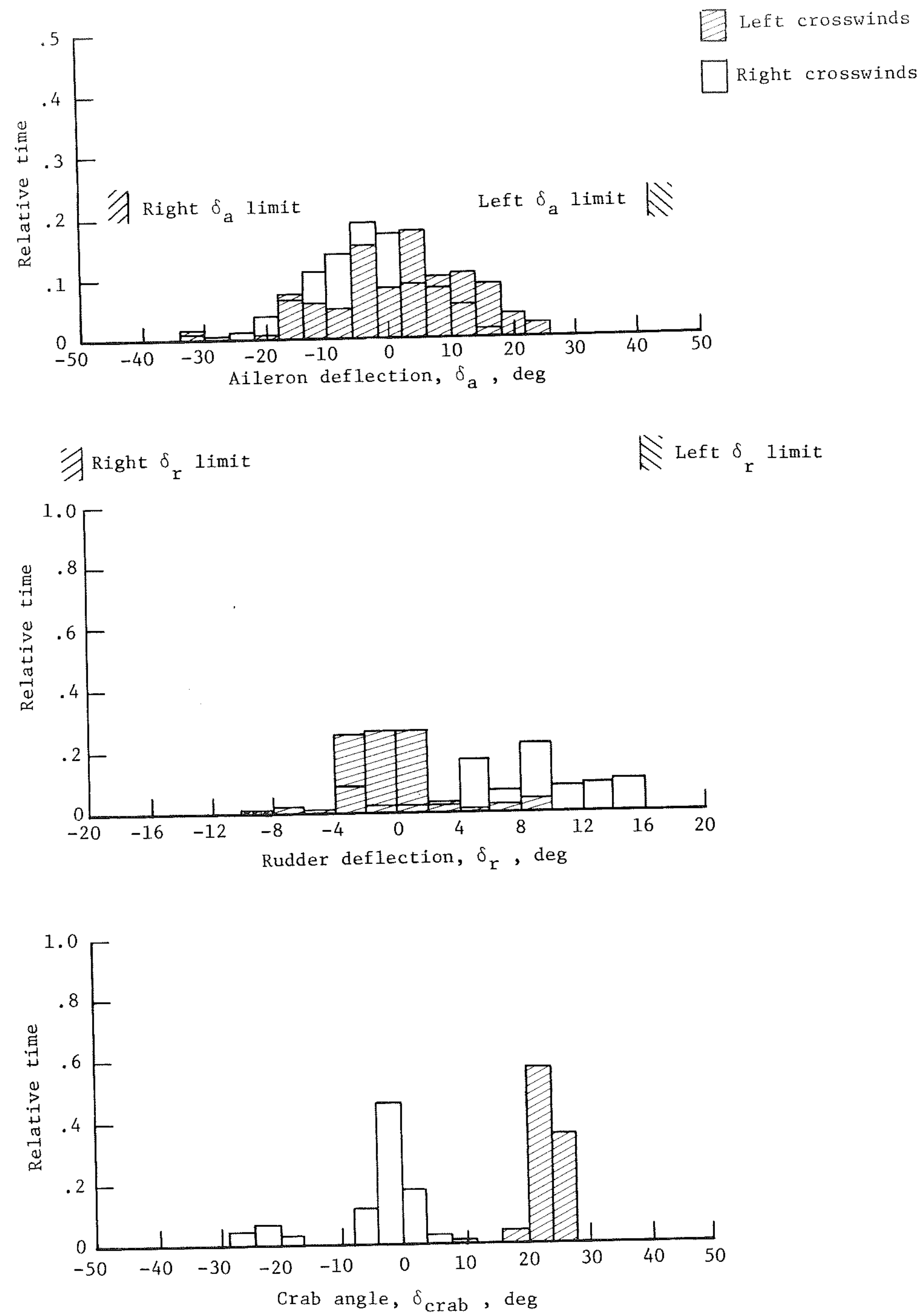


Figure 22.- Ground-roll distance. Data combined for all crosswinds, pilots, and both approach angles.



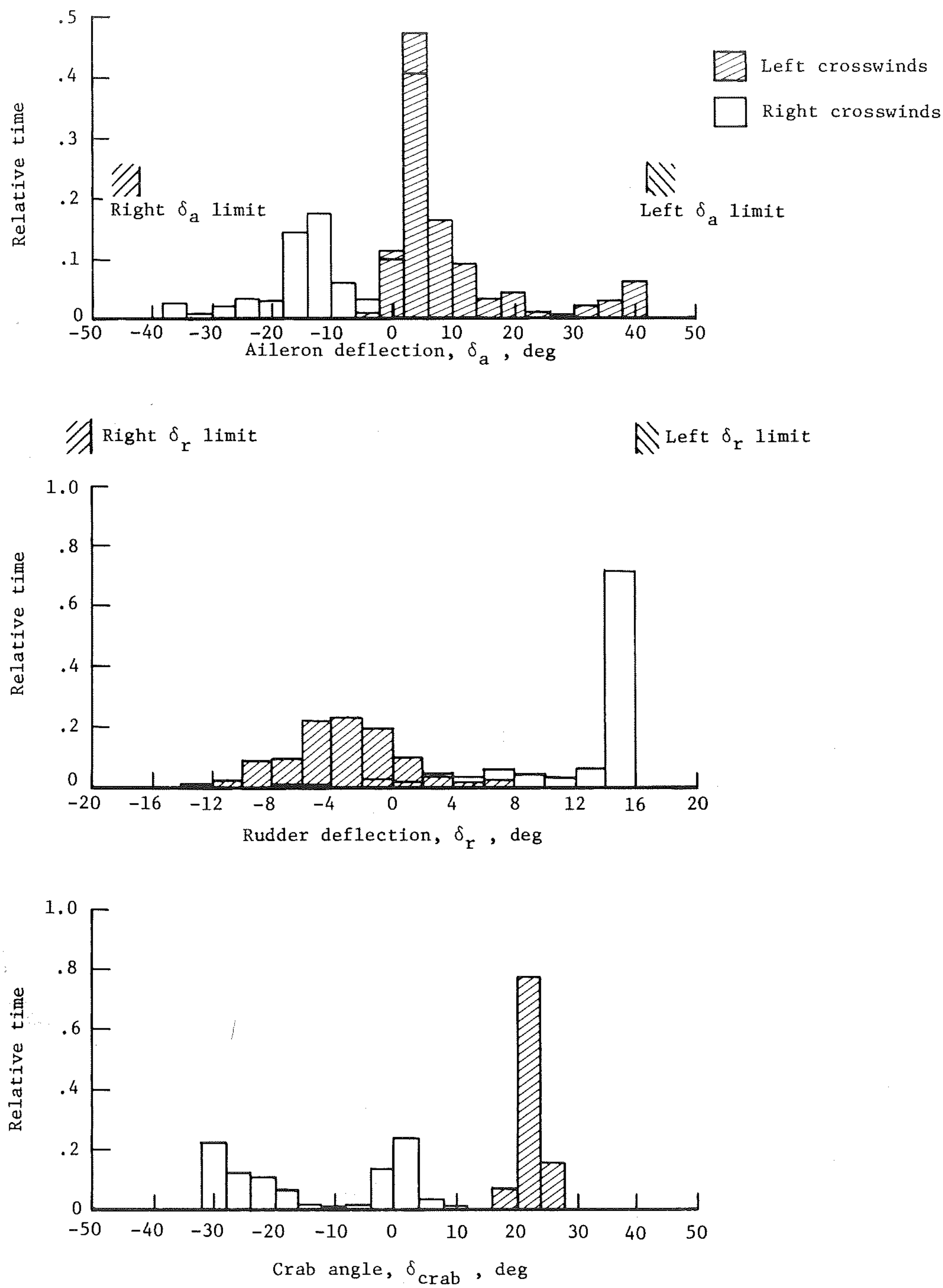
(a) Approach phase.

Figure 23.- Aileron deflection, rudder deflection, and crab angle histograms from castor-mode landings with crosswinds from 25 to 30 knots.



(b) Flare phase.

Figure 23.- Continued.



(c) Roll-out phase.

Figure 23.- Concluded.

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TP-1423		

4. Title and Subtitle	5. Report Date
FLIGHT INVESTIGATION OF PILOTING TECHNIQUES AND CROSSWIND LIMITATIONS USING A RESEARCH-TYPE CROSSWIND LANDING GEAR	May 1979
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Bruce D. Fisher, Perry L. Deal, Robert A. Champine, and James M. Patton, Jr.	L-12682
9. Performing Organization Name and Address	10. Work Unit No.
NASA Langley Research Center Hampton, VA 23665	505-08-33-12
	11. Contract or Grant No.
12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
National Aeronautics and Space Administration Washington, DC 20546	Technical Paper
	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

A research-type crosswind landing gear was tested by NASA in a flight program which used a light STOL transport in strong crosswind conditions. This study was a continuation of an earlier program which used the same airplane with conventional, tricycle landing gear. The research-type crosswind landing gear used in the present program enabled the airplane to land in crosswinds up to a magnitude of 25 to 30 knots. In the previous program, landings were accomplished in crosswind magnitudes only up to 15 to 20 knots. Three modes of landing-gear operation were investigated: preset, automatic, and castor (passive self-alignment). Actual test data and histograms are given for the 195 VFR crosswind landings made for this program.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Aircraft operations Crosswinds Crosswind landing gear	Unclassified - Unlimited Subject Category 02

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	52	$5.25

* For sale by the National Technical Information Service, Springfield, Virginia 22161

NASA-Langley, 1979